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Technical Note N-1091

NUCLEAR ELECTROMAGNETIC PULSE PROTECTIVE MEASURES APPLIED TO A TYPICAL COMMUNICATIONS SHELTER

By

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April 1970

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NUCLEAR ELECTROMAGNETIC PULSE PROTECTIVE MEASURES
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YF 38.534.006.01.015

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ABSTRACT

A detailed study of a typical communication facility has been made to determine the requirements for the installation of nuclear electromagnetic pulse (NEMP) protection measures. Necessary hardening measures have been determined on the basis of a single point failure analysis and the assignment of priorities to the various systems and components encountered.

Protective measures have been applied to power control and signal lines entering and within the complex as well as to electrically powered life support systems. NEMP hardening techniques and methods have been applied to non-electrical shelter penetrations as necessary and other applicable areas within the facility such as non-strategic lines, grounding systems, and cable routing.

Updated protective measures and NEMP hardening design parameters are provided in the appendix to this report including new techniques of inductively loading long shelter penetrating conductors to more effectively remove conducted pulses.

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1.0 INTRODUCTION

This study was undertaken to develop means of protecting the electrical power and supporting systems of an existing communication shelter against the electromagnetic effects of nuclear weapons (NEMP). The NEMP effects consist of rapidly changing electric and magnetic fields which cause transient voltages and currents to be induced in electrical systems. In this study, the shelter to be protected had been built before the NEMP effects were well understood and the importance of protecting against these effects evaluated. Since the shelter was already in existence, the protective measures to be developed had to be of such a nature that they could be adapted to the site without a prohibitive cost and without unduly interfering with the operations of the shelter.

The consolidation of pertinent information applied to hardening a facility with a large variety of communication control and operational functions forms the basis of this report. The techniques used to provide protection from NEMP effects in this facility study can be utilized as engineering guidelines for the NEMP hardening of other existing communication centers as well as a valuable guide in the design of NEMP hardening measures in new facilities.

One of the objectives of this study is to prepare a single point failure potential analysis of the shelter and its immediate environs. The purposes of this analysis are to identify problem areas, describe the kind of failure that may be caused by the problem, place a judgment rating on the seriousness of the potential failure, and describe the recommendations to eliminate the problem and the potential for failure. Ideally, this analysis should cover not only existing problem areas, but potential problem areas and conditions which are satisfactory now but which, by virtue of innocent changes in the site, might become problems in the future.

For any problem area an estimate of the seriousness of the problem is made. The seriousness is described by the subjective judgment of the reviewer subject to the following guidelines:

Priority 1 Condition

A condition which could cause destruction of the site, a condition which could cause major equipment damage of such magnitude as to force

a cessation of operations for times ranging from days to indefinitely, or a condition which could cause loss of life or serious injury to personnel.

Priority 2 Condition

A condition which could cause damage to major equipment and force it to be replaced from stocks maintained for that purpose, a condition which could cause cessation of operation for times on the order of hours, or a condition which would allow operation only under severe hardships to the personnel.

Priority 3 Condition

A condition which would cause damage to expendable items, a condition which delays operations for times ranging from a few minutes to one hour, or a condition which causes severe inconvenience but no real hardship for the personnel.

The single point failure potentials were broken down into the following categories: Power System, Grounding, Blast Closures, Environmental Control, Non-Strategic Cable Entries, Penetrations, Strategic Cable Entries, Internal Communications, Elevator, and Miscellaneous.

Figure 1 shows a simplified model with basic conditions most typically encountered when studying the NEMP protection of a shelter system. The figure shows a shelter partly buried into which power conductors and a signal cable enter. External to the shelter the power line and signal cables may be either above ground or buried; the problems involved are fundamentally the same, differing only in magnitude. Inside the shelter are three representative pieces of electrical apparatus, A, B, and C. None of the pieces of apparatus is directly connected electrically to the structural framework of the shelter, but are referenced to ground through an electronic ground system having a ground resistance R_E. At point F, the framework of the shelter is connected to a buried grounding network through a building ground system having a ground impedance R_B.

As a result of an atomic detonation, the shelter is exposed to a changing electric field E and a changing magnetic field H. Typically, the shelter was not designed to provide electromagnetic shielding. As a result, there will also be changing electric and magnetic fields, E' and H', inside the shelter, having amplitudes proportional to the amplitudes of the fields external to the shelter.

The result of changing magnetic fields inside the structure will be induced voltages around loops such as ABCA. If the loop is closed, the induced voltages will cause circulating currents around the loop. If the loop is not closed, voltages will appear across the open points in the loop. These voltages and the resultant breakdown and arcing may be sufficient to damage pieces of electronic apparatus.

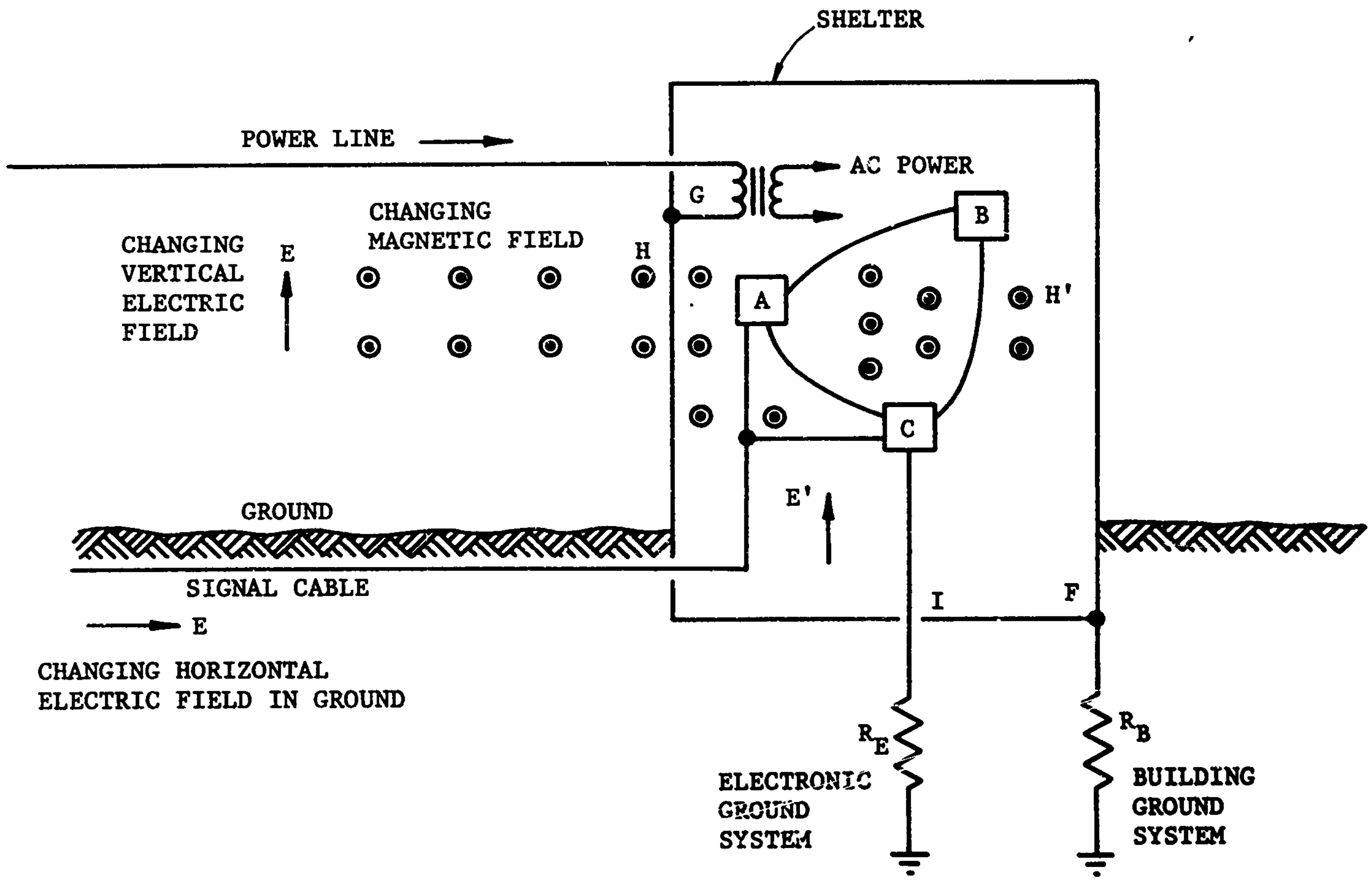

Figure 1. Typical problem areas.

The external electric or magnetic field can induce a surge on the power line conductors coming into the shelter, coupling through transformers, and impressing a surge voltage onto the apparatus connected to this source of power.

Currents induced in the ground by the horizontal E-field component of the NEMP wave can become concentrated on buried cables such as the signal cable and flow directly into the shelter and into pieces of electronic equipment like A and C. There is an available path for the pulse current to flow through the electronic apparatus and to ground through the electronic ground system. As the current surges through impedance R_E, it raises the potential of the interconnected systems A, B, and C relative to the potential of the shelter. The potential of the shelter would be determined by currents flowing through the building ground system which are typically isolated from the electronic ground systems. The building potential would be determined by the potential of the building ground system and currents flowing through it. Consequently, there could be very large voltage differences between the electronic systems and grounded portions of the shelter or voltages from points B to F or C to F.

Some of the more important techniques used to protect systems against NEMP are shown on Figure 2. The following is a list of some of the things that have been changed from Figure 1 to give the protected system shown on Figure 2.

First, the shelter has been modified to provide shielding against the external electric field. On existing structures it is generally not feasible to provide totally enclosed shielding for electronic equipments against such fields, but it is always possible to obtain some degree of shielding by increasing the electrical interconnections of the structural members of the shelter. For example, the reinforcing bars in structural concrete provide some degree of shielding, and in many cases these bars were welded together at cross-overs during the construction of the shelter.

Second, wiring within shelter is typically run in metal conduit or cable trays. These conduits and trays should be interconnected and electrically tied to the structural grounding system allowing currents to flow and disperse on the metal parts of the structural system. The best conductor shielding against NEMP is obtained through the use of rigid steel conduit. In decreasing order of shielding effectiveness would be thin-wall conduit (E.M.T.), flexible tubing equivalent in shielding to Sealtite, braided shields, wrapped aluminum or copper foil shields, armored cable (BX), and metal covered cable trays. RFI-type covered cable trays could be made to approach rigid conduit in shielding effectiveness.

Third, all of the electrical apparatus is bonded to the metal structure of the shelter through electrical bonding connections of the minimum practical length. These bonding connections should be made at as many points within the shelter as feasible.

Fourth, the electronic ground system has been connected directly to the building ground system by means of a jumper at the point I. Existing

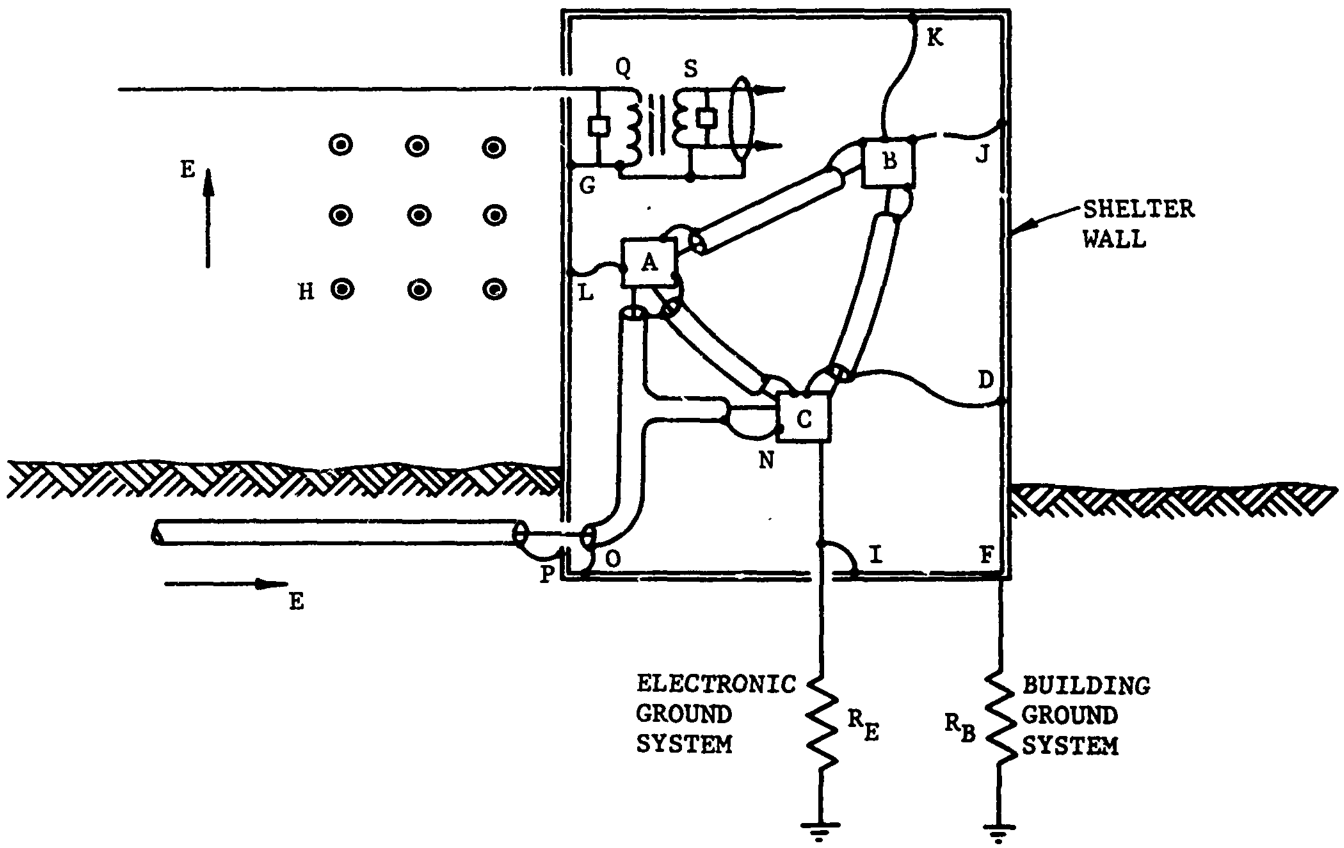

Figure 2. Typical approaches to protection against NEMP fields.

separate grounding systems are always a prolific source of trouble when providing NEMP protection.

Fifth, the electric power system has been protected with protective devices at points Q and S to G. These protective devices are designed to limit the transient overvoltages that would be present on the electric power system.

Sixth, the external communication line which is normally carried in a shielded line has its shield connected to the building metal structure and ground system at the point where it enters the shelter. The purpose of this ground connection, such as at points P and O, is to provide means for induced currents flowing on the shield of the communication cable to go through a low impedance path directly to ground without flowing inside the shelter on the electronic apparatus and then to ground.

Low grounding impedance for the shelter metal structure is desirable because it limits the rise in potential of the shelter above the external reference ground system when NEMP induced currents flow through this ground system to earth. However, low ground impedance, per se, does not insure an absence of harmful effects from NEMP. Of more importance than low ground impedance is the degree of bonding or interconnection within the structure that will insure that all points within the shelter ride up to the same potential relative to each other and the structure. With sufficient attention to the degree of bonding and shielding within the system, the system can be effectively contained within a Faraday cage. Within a true Faraday cage the grounding potential differences are zero, even though the potential of the entire system may be high relative to some external reference ground system.

In later sections of this report considerable attention is given to the subject of interconnection between metal piping, metal conduit systems, and the metal structural members of the shelter. The intent of these measures is to insure that induced currents entering or flowing in the shelter flow in as diffuse and evenly distributed manner as possible. As much as possible connections should be provided to allow the currents to flow outward into the reinforcing steel within the walls and metal framework. Even with less than ideal connections between the various reinforcing steel bars, induced surge currents will tend to be distributed around the exterior walls of the shelter. The more they become uniformly distributed, the more the electromagnetic fields within the shelter caused by the flow of these currents would tend to be reduced or cancelled. Even when the induced current distribution is not uniform by allowing the induced currents to flow on exterior wall portions of the shelter, these currents would be as far removed from the electronic equipment to be protected as possible. Then resultant magnetic fields generated by these currents would be lower at the electronic equipments.

The currents induced by NEMP may have very rapid rates of change. If these currents flow through even moderate inductances, they will develop appreciable voltage across this inductance. Thus, it is desirable that all bonding and grounding connections be as short and multiple as possible and run between points as nearly in a straight line as feasible

to keep inductance low. In the recommendations to follow in this report, the following wire sizes are recommended:

Ground Rings around a room should utilize conductors at least as large as #2AWG copper conductor or copper strap 1/8" thick by 1/2" wide. Mechanical considerations usually dictate a copper strap at least 1" wide.

Flexible Bonding Strap should be used to connect metal chassis or cabinets to the ground ring with conductors equivalent to #6AWG copper wire, or larger.

Where flexibility is needed, the grounding connections may be stranded or of copper braid.

In locations where they are exposed to moisture, dissimilar metal connections should be used with caution since electrolysis problems may develop and connectors and connections should be suitably weatherproofed.

The AC power circuit distribution system will be protected by a combination of shielding and surge suppression devices. (See Appendix A) The shielding is provided by the conduits containing the power conductors and the cases of the power distribution transformers and switchgear. Lightning type arresters will be used to protect the high voltage primaries of transformers and will be of the type suitable for connection at the transformer location. Typical values of the clamping voltage of available lightning arresters are:

1. 12 to 16 KV for arresters suitable for 4160 volt systems, and

2. 2 to 4 KV for arresters suitable for 480 volt (and lower) systems.

The exact clamping voltage which results will depend on the wave shape of the incoming surge and on the peak value of the surge current; this latter in turn depending on the impedance of the power circuit and the mechanism that generates the surge.

Typical commercial lightning arresters for 120 volt circuits do not clamp to voltages below approximately 2,000 volts because they depend on a spark gap which, for practical gap sizes and under fact transient conditions, cannot flash over at less than about 2,000 volts. Consequently, nonlinear protective devices will be used to control transients on the low voltage circuits. Thyrite* disks will be used to control surge voltages on 480 volt circuits, while Thyrectors** or similar

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*Thyrite - Registered General Electric Co. trade name. A silicon carbide material, nonlinear resistance type protective device.

**Thyrector - Registered General Electric Co. trade name. A silenium rectifier-type protective device.

selenium devices will be used to control voltage surges on 120 volt circuits. The Thyrectors should be installed in the power inputs of electronic equipment as close to the equipment as possible. The equipment power fuse block may be a good location providing access to the power conductor. A Thyrector installed in one rack would tend to protect equipment on adjacent racks as long as they are fed from the same power circuit. To provide the best degree of protection, Thyrectors will be installed in each piece of equipment.

The following items have been analyzed and are discussed on the basis of a Fault - Remedy approach. This technique is directly applicable to the specific cases presented, but it may also be possible to apply similar protective fixes and logic to related situations not directly analyzed.

2.0 POWER SYSTEM

A. UTILITY POWER AND POWER DISTRIBUTION SYSTEM

Priority 1

<u>Fault</u>. The incoming three phase delta power conductors leave a pothead on the utility pole in a lead-covered cable which is carried in a buried four-inch non-metallic conduit into the shelter. Inside the shelter the conduit ends and the lead-covered cable continues to the delta to delta transformer. When the NEMP field engulfs the structure, it also engulfs the outside transmission line loop to ground.

An induced pulse of current will flow in the three-phase power transmission line loop with ground return. In addition, the NEMP induced E-Field may cause the lines to ride up in voltage with respect to ground and existing lightning arresters may spark over. The resulting current and voltage transients will be conducted into the shelter and coupled through the step down transformers. Coupling will be both through the magnetic structure of the transformers as well as through the capacitance between primary and secondary windings. Surges will propagate along the internal power distribution system, modified by reflections at the utilization equipment. The possibility exists that voltage and current transients at the utilization equipment may be larger in magnitude than the transients passing through the transformers.

These transients may be high enough to damage strategic electronic equipments. A priority rating of one is applied because of the possibility of widespread electronic system damage.

<u>Remedy</u>. (1) - Preferred, but most expensive solution.

A. Replace the delta to delta generator vault transformer, with a delta-wye transformer having an electrostatic shield between windings.

B. Place lightning arresters on the primary side of the transformer. The arresters should be grounded to the transformer tank and should be enclosed in a metal enclosure for electromagnetic shielding. Radio Frequency Interference (RFI) tight seals should be used on the doors to the enclosure.

C. The transformer tank should be grounded to the system ground bus.

These recommendations are shown on Figure 3.

Remedy. (2) - Alternate solution providing good protection at less cost.

A. Keep the existing vault transformer.

B. Place lightning arresters on the primary side of the transformer.

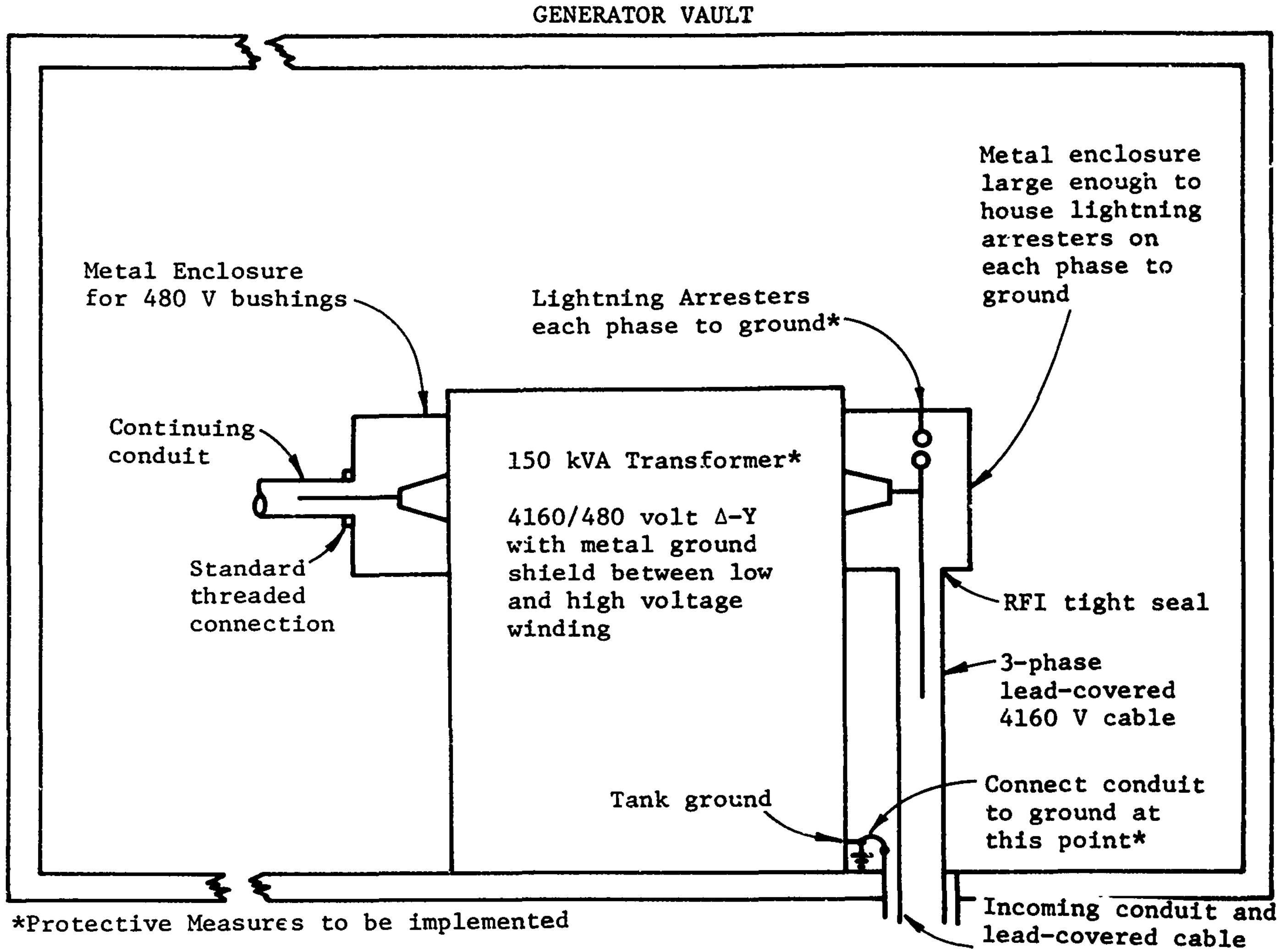
C. Ground the lead sheath of the cable where it enters the transformer vault.

D. Place lightning arresters and shunt capacitors between each of the secondary terminals and ground. These lightning arresters and shunt capacitors should be placed in a metal container for electromagnetic shielding. RFI tight seals should be placed on the doors of the container.

These alternate recommendations are shown on Figure 4.

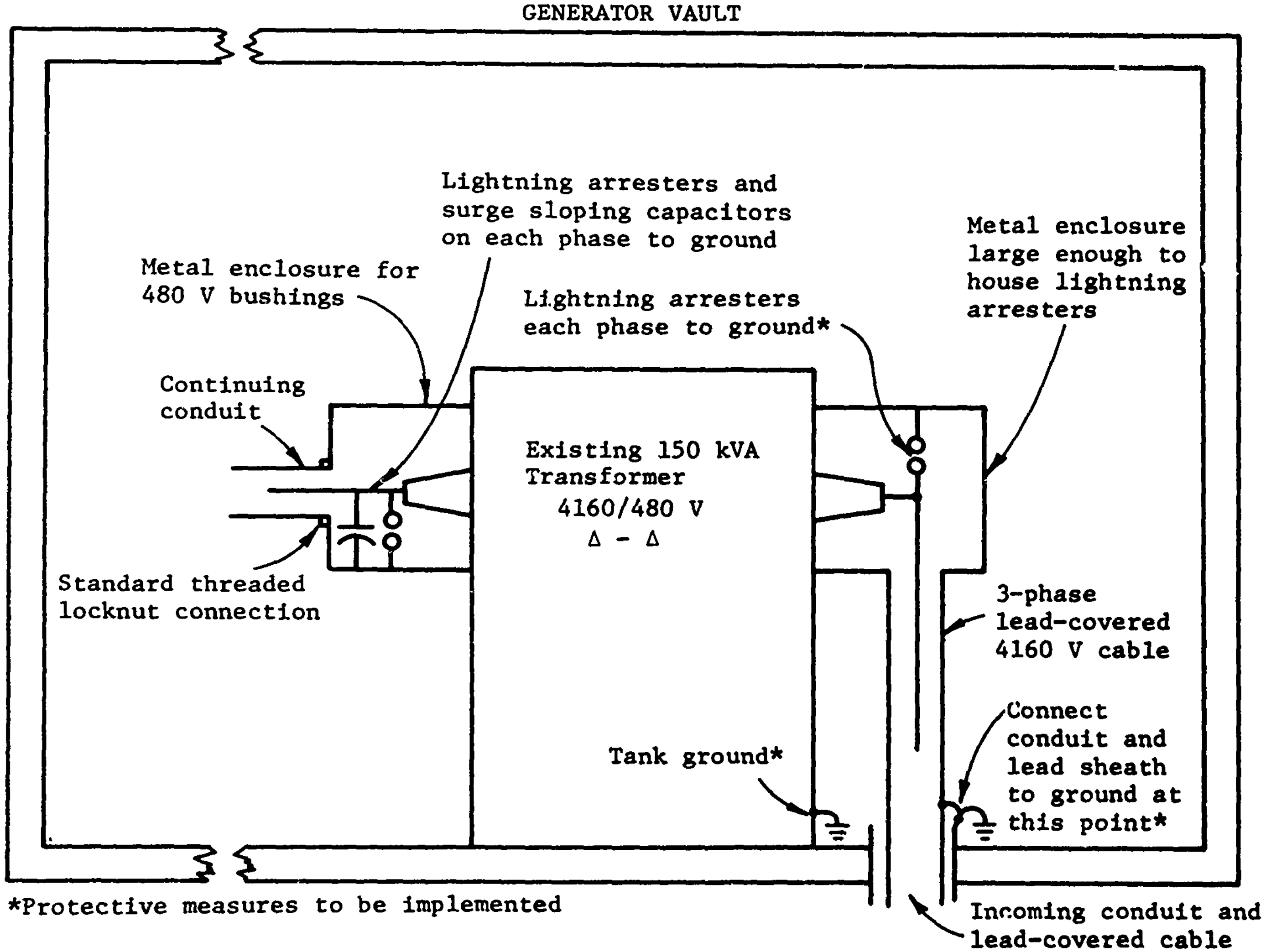
Remedy. (3) - Place Thyrectors on power circuits of all essential electronic equipment. These should be connected from each line-to-ground and from line-to-line. The best location for these Thyrectors would be at the fuse block where power is brought into each electronic equipment rack. The Thyrector elements connected line-to-ground should be grounded directly to the equipment racks through ground leads of minimum length. A second choice for location of these Thyrectors would be in the switch and fuse box serving the equipment if the run to the equipment is shielded in conduit.

As an alternate to mounting the Thyrectors permanently, it would be satisfactory to install them within a metal case having a short cord with a standard three-terminal, 115 volt AC plug. The case could be bolted to the equipment rack and the cord plugged into the power receptacle serving the equipment to be protected. Steps would have to be taken to ensure that the plug is never removed. Connections and a possible mounting arrangement are shown on Figure 5.



*Protective Measures to be implemented

Figure 3. Preferred method of treatment of incoming 4160 volt cable in the generator vault.



*Protective measures to be implemented

Figure 4. Alternate treatment of incoming 4160 volt line in the generator vault.

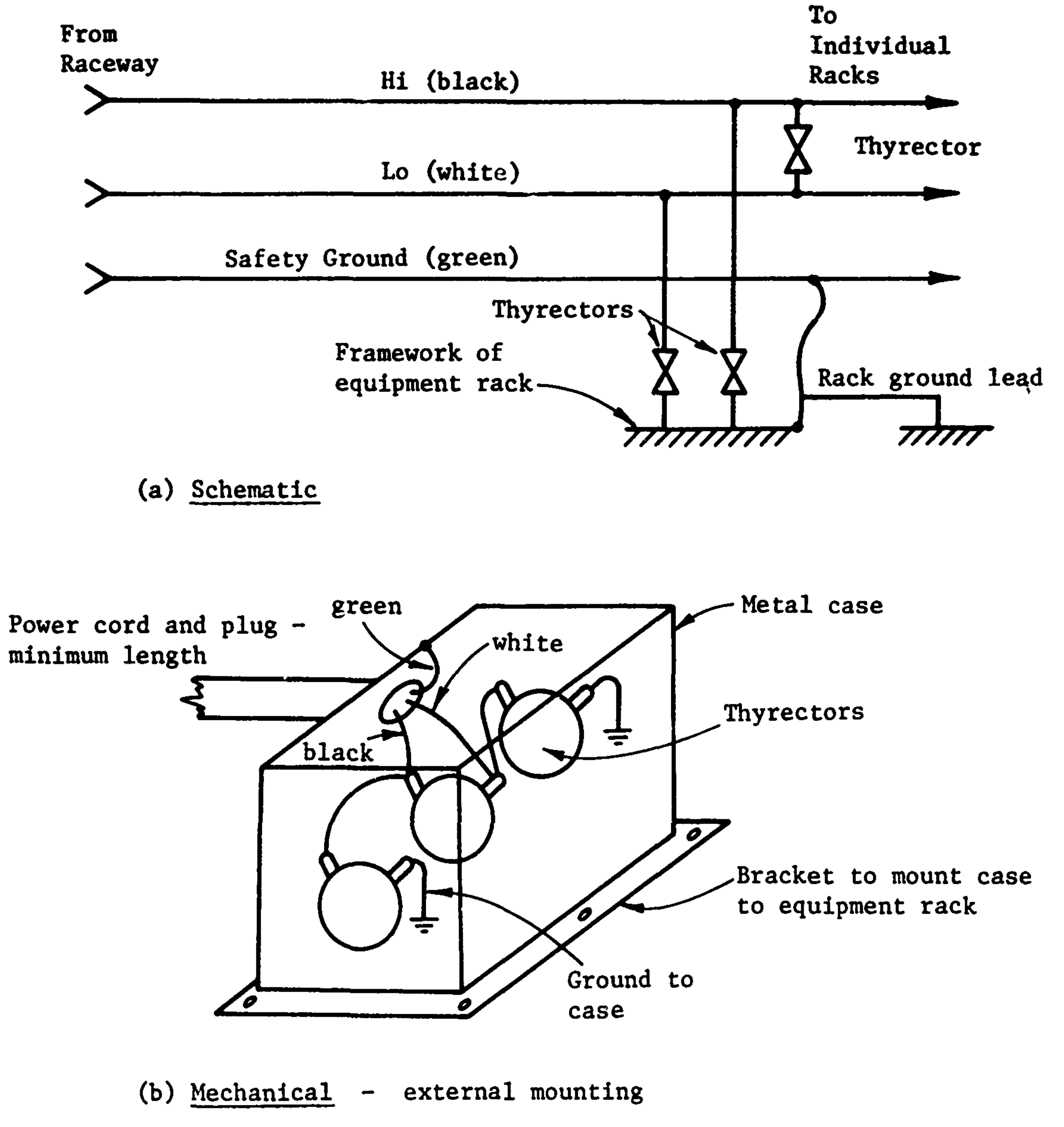


Figure 5. Thyrectors to protect electronic equipment in racks

B. OVERHEAD 208/120 VOLT POWER LINES TO A TEMPORARY STRUCTURE

Priority 2

Fault. A 208/120 volt circuit is exposed to the field environment. The wiring leaves an outside conduit near the shelter entrance at approximately a height of 12 feet and extends 30 to 50 feet overhead to a temporary structure. The power is used to provide heat within the building.

Since this wiring is exposed to the field environment, high voltage effects from both the E-Field and H-Field would be injected into the power system before the external wiring and the temporary structure would be demolished. These transients would be coupled directly on the internal distribution system if this circuit is connected to the output of the 150 KVA transformer serving the shelter.

Remedy. The wiring for this heater circuit should be contained in its entirety in standard rigid steel conduit underground from the vault to the temporary structure. Condulets* should not be used at the point where this conduit leaves the vault; it should be connected to the ground system or structure ground by a short metal bonding strap. Where the conduit connects to the heater within the temporary building, a metal junction box should be installed. In this junction box, Thyrite or Thyrectors should be connected between each line and the box.

C. COMMUNICATION POWER ELECTRICAL RACEWAYS

Priority 2

Fault. Communications power comes from the main power panel (MP) to the various shelter floors in rigid metal conduit. At each floor the conduit ends in a power panel. From the power panel on each of these floors, the communications power wiring is run in conventional wireways from which BX cable, E.M.T., or Sealtite is used to connect to the various electronic consoles. The wireways and BX do not provide adequate shielding.

Remedy. All BX cable should be replaced by Sealtite flexible tubing. Sealtite installations should be checked to be sure that electrical contact is made between the Sealtite tubing and the conduit and

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*Condulets - Any conduit fitting which has other than a threaded means of connection or any box whose cover is held in place by screws. These devices normally have a rubber-type gasket between the cover and the main body of the condulet. This reduces the shielding effectiveness of the device unless the rubber gasket is replaced with an RFI type gasket.

boxes to which it connects. If not already installed, any routing wireway should be replaced by RFI cable tray or rigid conduit. If conduit is used, the flexible Sealtite enclosed drop leads would come from junction boxes located over each electronic console. Thyrectors should be connected between each power lead and grounded cabinet at the fuse clip inside the equipment cabinet. (Refer to Figure 5.)

D. POWER DISTRIBUTION TO ANTENNA ROTATORS

Priority 2

<u>Fault</u>. The rotator control wiring for two beam antennas come from an external exposure into the shelter and into a control panel on the left-hand end of the communications rack. From this panel they are wire plugs into the power plug strip. This is a prime place for surge voltages induced externally to the shelter to be injected directly into the power feeding the communication equipment.

<u>Remedy</u>. Enclose the rotator control wiring in its entirety in rigid ferrous conduit grounded at the point where it enters the shelter. If compatible with the roter control system, feed the rotator power through an isolation transformer (with grounded electrostatic shield) and a separate circuit from the distribution box. Thyrectors should be installed between each power lead and ground at the first available location after it enters the shelter.

2.1 EMERGENCY POWER SYSTEM

A. EXPOSED WIRING IN THE DIESEL STARTING SYSTEM

Priority 1

<u>Fault</u>. In the event of utility power failure, the emergency power unit starts automatically. Starting is accomplished by a 24 volt battery system. The signal which energizes the starting system comes from a power panel inside the shelter. The wiring from the power panel to the generator is routed in rigid steel conduit. The wiring from the starting panel to the motor starting solenoid is exposed at the diesel engine. Also, the battery and the battery leads to the starting motor are unshielded.

The voltage transients induced on the open wiring due to exposure to electromagnetic fields may cause damage to the starting motor and/or starting solenoid or may cause secondary damage to other circuits in the control panel.

The proper operation of the emergency generator is very important and, therefore, no open wiring should be permitted. Loss of the starting system for the diesel engine would mean loss of the entire emergency power system.

Remedy. Several methods can be used to shield the open wiring.

1. Battery Circuit
   Use a shielded enclosure for the battery and Sealtite for the battery cables. See Figure 6.

2. Starter Solenoid Wiring

   A. Use shielded leads from the nearest junction box to the solenoid, grounding shields at their terminations.

   B. Tightly wrap present leads with metal foil tape, using halfwrap overlapped and ground the tape at terminations. Cover metal foil tape with electrical tape.

   C. Provide a metal enclosure around starting motor and solenoid and use Sealtite for wiring to the nearest junction box.

   D. Enclose present leads in shielded zipper tubing, grounding the shielded tubing at the termination.

Any one of the above methods of shielding would be satisfactory.

B. EXPOSED WIRING ON TROUBLE INDICATING CIRCUITS

Priority 2

Fault. The diesel engine has several trouble light indicating circuits which go to a master control panel. The wiring is routed in rigid steel conduit except at the diesel engine where the wiring is exposed. Voltage transients induced on the open wiring may cause these circuits to malfunction giving a false indicating signal which could possibly initiate shutdown of the emergency power unit. If malfunction of these trouble indicating circuits does not cause automatic shutdown of the generator, the priority may be downgraded to three.

Remedy. Because of the critical nature of the emergency power unit, the exposed trouble indicating light wiring should be shielded.

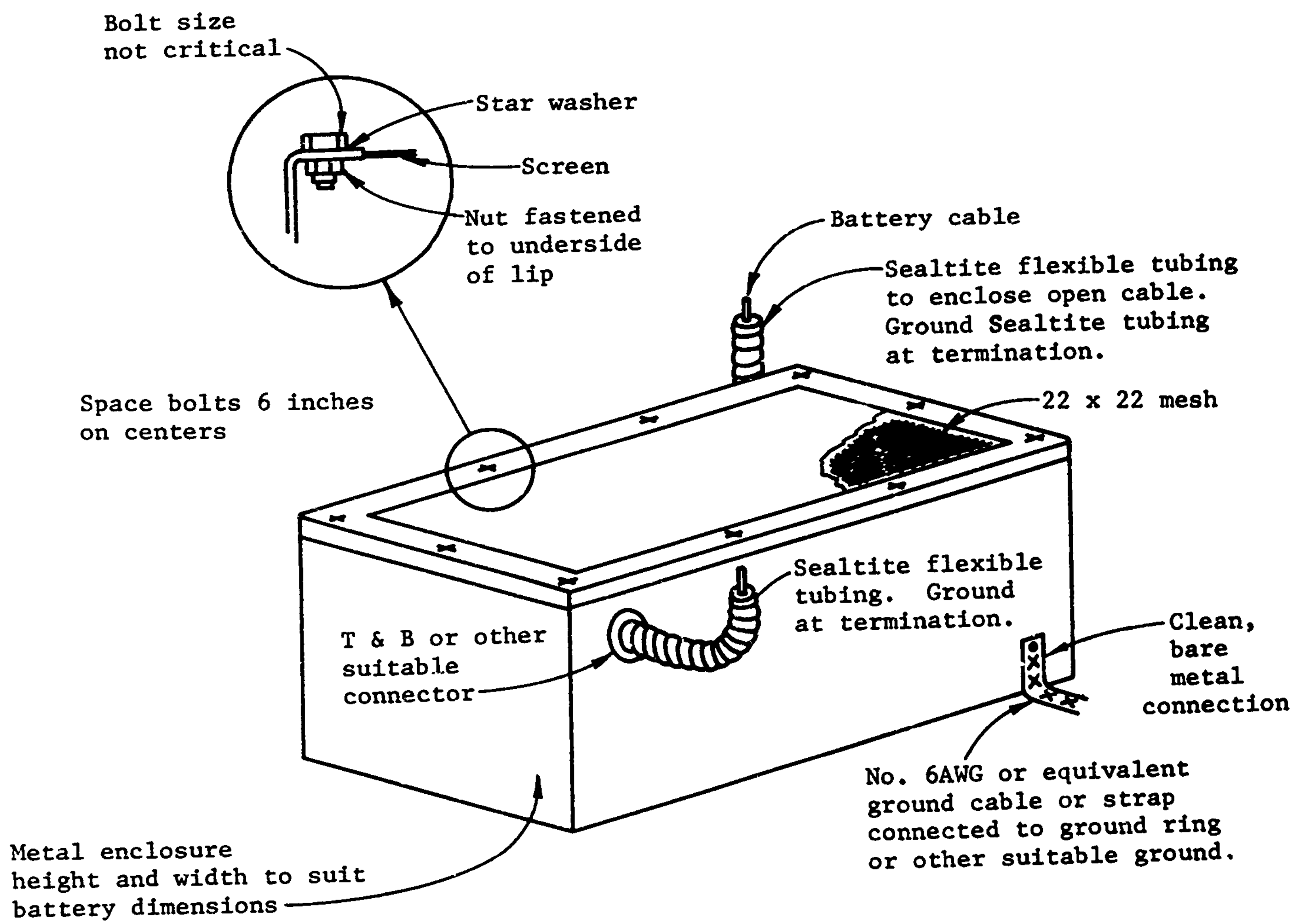


Figure 6. Shielding of battery and associated wiring in diesel starting circuit.

C. MAIN POWER CONTROL CABINET

Priority 2

<u>Fault</u>. The main power control cabinet houses, among other things, the automatic transfer switch. The doors on this cabinet are hinged on the sides and close by means of a center latch. The door does not fit very tightly and the mating door flange and cabinet surfaces are painted.

Leakage flux into the cabinet could cause high voltage transients to appear across the transfer switch. Voltage transients will also appear on the transfer switch coming from utility power circuits. Interaction of these transients may cause transfer switch flashover and, consequently, failure of the switch to operate.

<u>Remedy</u>. In order to protect all the wiring in this cabinet from having unduly high voltage transients induced on it, the cabinet doors should be made RFI tight. This involves the following (see Figure 7):

1. Remove paint from door and cabinet mating surfaces.

2. Install an RFI gasket on these surfaces.

D. NON-METALLIC FLEXIBLE JOINTS IN DIESEL FUEL LINE

Priority 2

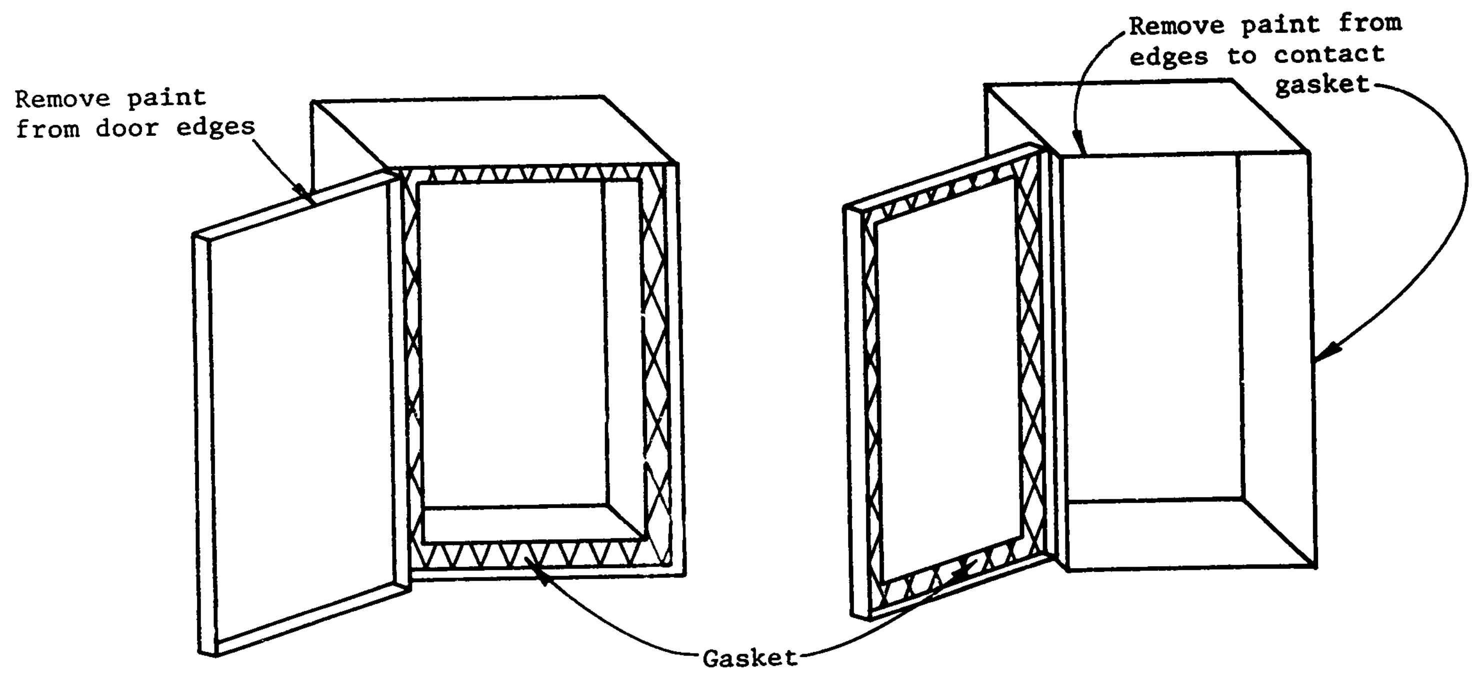
<u>Fault</u>. Diesel fuel is carried in metal hose from the fuel tank to the vault area. Connection of these lines to the diesel engine is done by rubber hose. Rapidly changing magnetic fields can induce high voltages around conducting loops formed by the fuel lines and the ground system. These high voltages can cause sparking across the rubber joints. Sparking may not be harmful, but if flammable vapors are near, the spark could set off a fire and shut down the diesel.

<u>Remedy</u>. Connect a flexible ground strap across the joints. This strap may be copper braid, 0.25" or wider, and a length just long enough to make a flexible connection. See Figure 8.

E. NON-METALLIC FLEXIBLE JOINT IN ENGINE EXHAUST AIR DUCT

Priority 3

<u>Fault</u>. The engine exhaust air duct has a flexible non-metallic joint. Rapidly changing magnetic fields can induce high voltages across this joint because the joint opens the conducting loop formed by the metal ductwork and the ground system. Sparking across the joint could ignite flammable vapors.



1. Remove non-conducting gasket, if any, and replace with RFI gasket or copper braid.
2. Gasket must be in contact with bare metal surface.
3. Remove paint from edge contacting conducting gasket.

Figure 7. Installation of conducting gaskets on power cabinet doors.

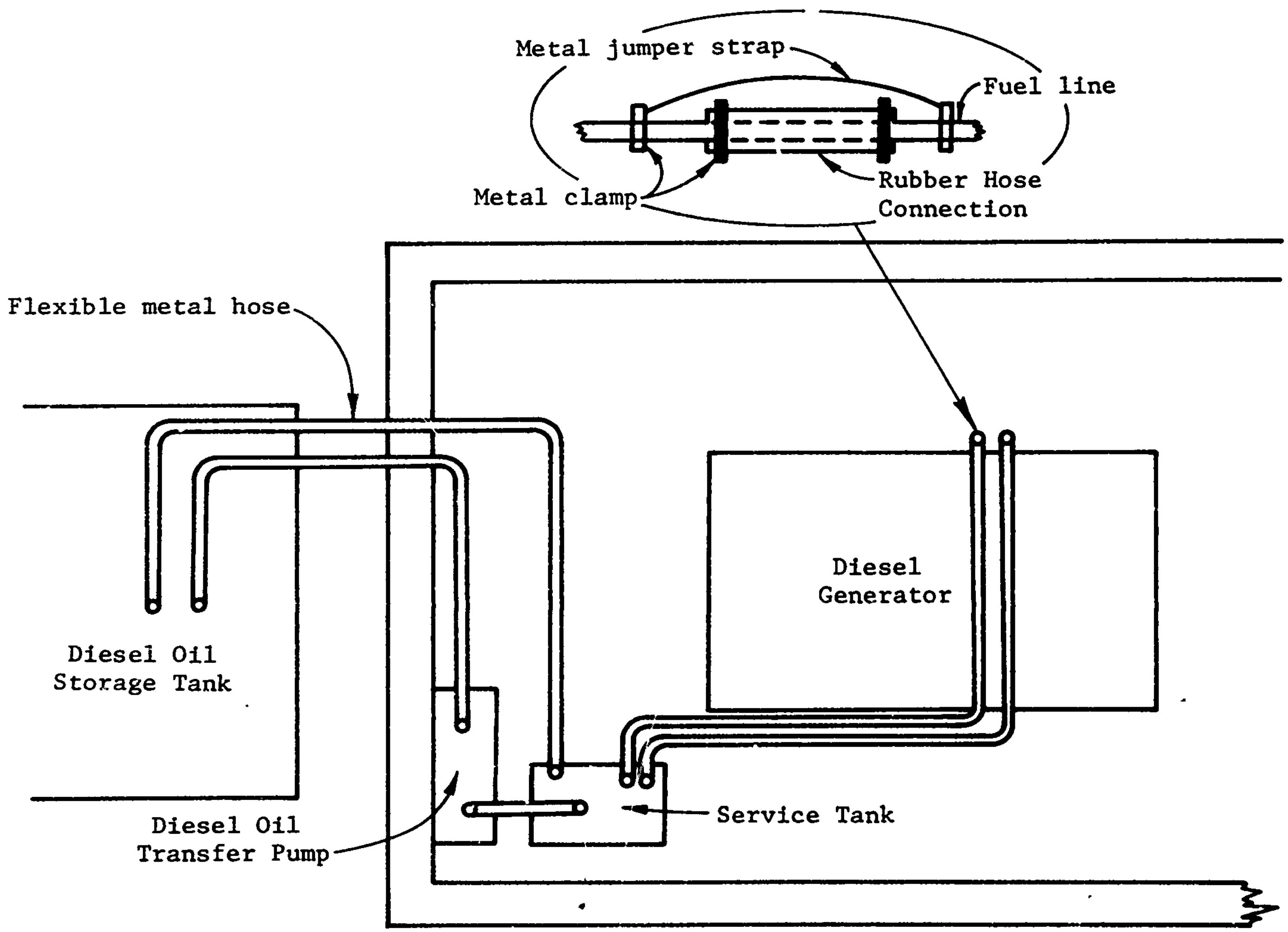


Figure 8. Metal jumper on fuel line.

Remedy. Connect a flexible ground strap across the joint. This strap may be copper braid, 0.25" or wider, and a length just long enough to make a flexible connection. There should be at least two jumpers per joint. See Figure 9 for an example of this technique.

F. EXPOSED STATION BATTERY

Priority 2

Fault. The station battery is exposed to the NEMP fields, and voltages induced in the wiring to the battery could damage the starting motors of the emergency generators or damage the controls for the circuit breakers.

Remedy. Connect a 1.0 μf capacitor from each of the positive and negative lines to ground as shown on Figure 10.

3.0 GROUNDING AND BONDING

A. GROUNDING OF METALLIC EQUIPMENT (ELECTRICAL AND NON-ELECTRICAL)

Priority 3

Fault. A number of items of equipment are not presently connected to the electrical grounding system. This equipment includes:

1. well pump
2. well pump starter
3. water transfer pump
4. power panels (3)
5. 150 kVA transformer
6. compressor
7. generator control panel
8. generator start panel
9. blast closure valves
10. blast closure valve control panel

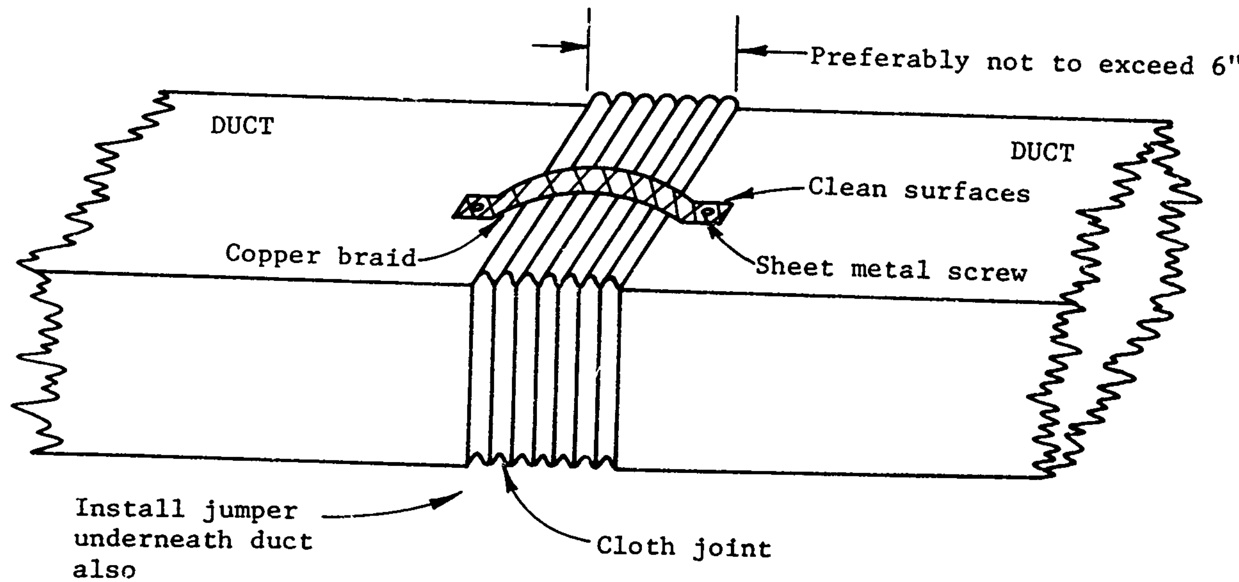


Figure 9. Connecting jumper across joints in air-handling ductwork.

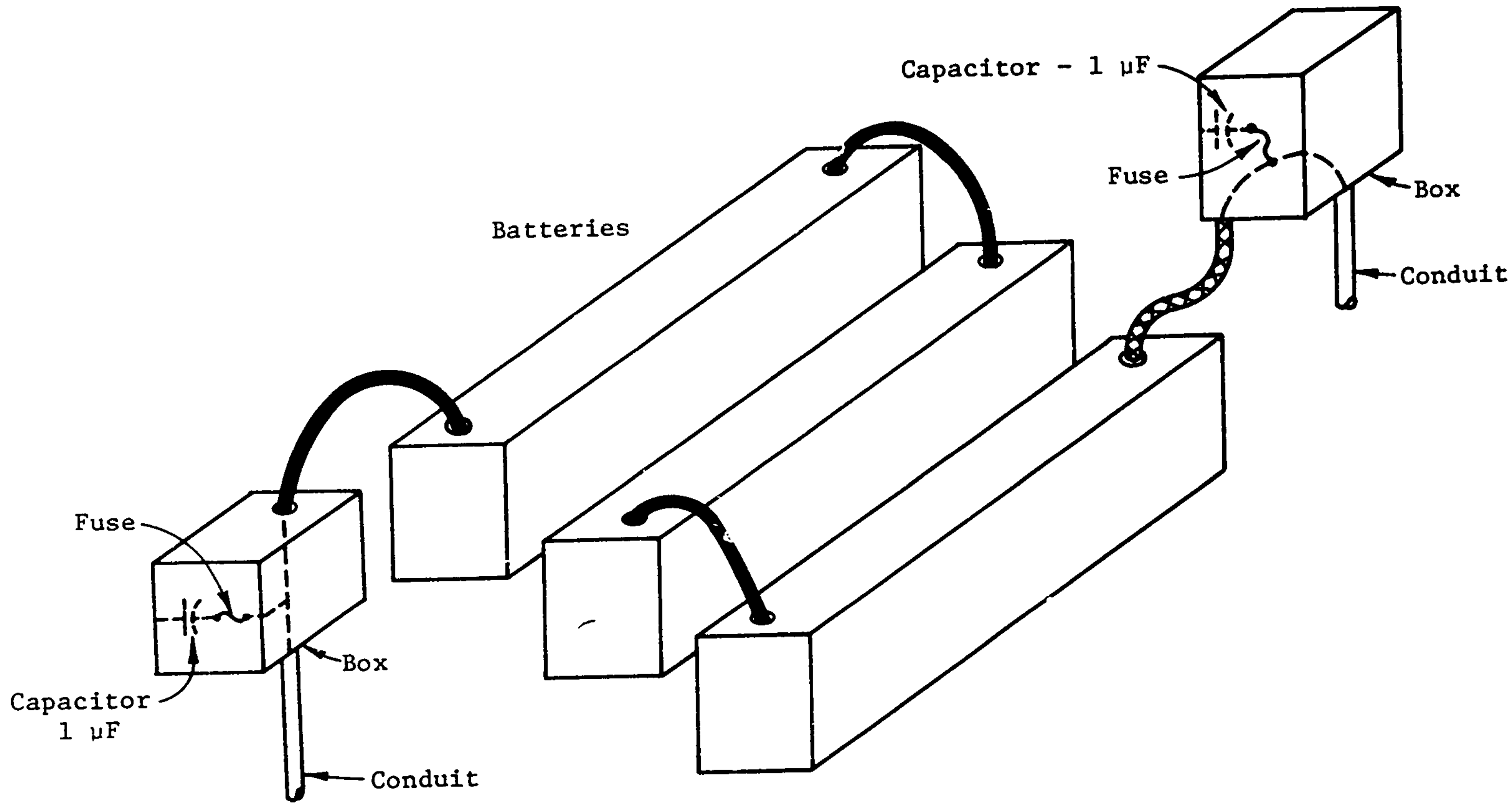


Figure 10. Capacitor protection of a station battery.

11. louver housing for intake valve

12. lubrication oil tank

13. exhaust air ductwork

14. water softener

Rapidly changing electromagnetic fields could cause arcing between pieces of equipment and between equipments and metal portions of the shelter structure. Current flowing on this equipment via conduit or BX could induce voltages on contained wiring.

Remedy. A copper strap grounding ring should be placed around the inside periphery of the generator vault and connected to the reinforcing bars (rebars) in the concrete wherever possible. The metal door frame is normally connected to the rebars and there may be other structural members accessible to which connections can be made. This copper strap should also be connected to the station ground grid with as short connections as possible. Each piece of equipment should be connected to the ground ring through conductors having cross-sectional area equivalent to a No. 6AWG or larger copper wire. These bonding straps should be of the minimum possible length. See Figure 11.

The copper ground ring strap shall have a cross-sectional area not less than a No. 2AWG cable. Mechanical considerations may dictate the use of a flat copper strap, ribbon, or braid. Strap dimensions should be one inch wide x 1/8" thick. This ground strap should not be enclosed in any type of conduit or electrical raceway, but should be electrically connected to metal piping, conduit and other metal work which it touches or closely approaches.

B. GROUNDING STRAPS CARRIED IN ELECTRICAL RACEWAY

Priority 3

Fault. In the communications area one of the communication cables enters a terminal box attached to the shelter wall. The outer shield of the communication cable is connected to a metal bus inside the box. The metal bus is connected to ground by a metal strap routed through conduit and wireway to a ground plate on the tower wall near the elevator. Since the ground strap must carry the induced pulse currents flowing from shield to ground, the ground strap will couple electromagnetic energy into the adjacent communication power circuits within the wireway, thereby inducing transient voltages on adjacent conductors.

Remedy. The grounding strap should not be enclosed in any electrical raceway but may be routed adjacent to the exterior of the raceway and

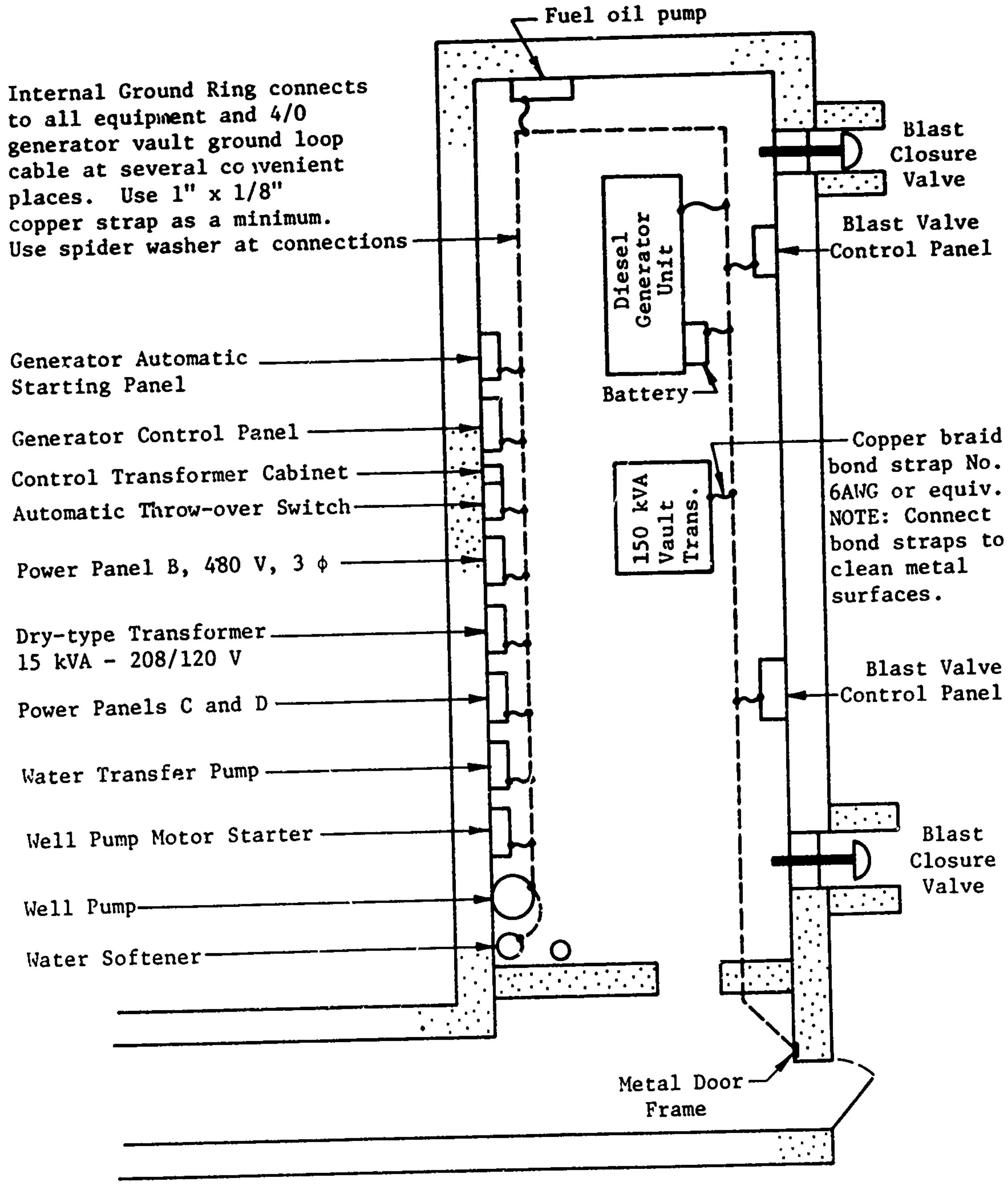


Figure 11. Grounding ring for generator vault.

inter-connected electrically to the raceway at numerous connections. The ground strap for the communication cable shield and the terminal box ground bus should be connected to a ground bus running peripherally around the shelter transversing over as many communication equipment cabinets as possible. The ground bus should be solidly connected to the wall ground wall plate and to structural steel at convenient places such as hatch door frames. Each communication equipment cabinet should be connected to this ground bus. See Figures 11, 12 and 13.

The ground bus as described should be installed on all floors housing communication or electrical equipment.

C. GROUNDING PLATE ON EACH FLOOR

Priority 3

Fault. The grounding plates on each floor are wall mounted and connected to a ground riser which supposedly is attached to the shelter building ground system. The communication equipment cabinets are not specifically connected to the ground plates nor is the ground plate specifically connected to reinforcing steel.

Remedy. A ground bus should be run from the wall ground plate directly over or near all equipment racks. Short bonding straps should be attached between equipment housings and ground bus. Attachment should be made to clean bare metal surfaces. See Figure 14 for guidelines on the grounding of electrical and mechanical equipment in the shelter.

D. INTERCONNECTION OF LIGHTNING GROUND AND BUILDING GROUND ON SHELTER ROOF

Priority 3

Fault. There are lightning rods and antennas on the top of the structure. In almost all cases, the antennas protrude above the level of the lightning rods. Consequently, if this site is hit by lightning, it will hit one of the antennas.

Although construction specifications for the shelter has stated that the internal grounding system and the lightning grounding system should be electrically isolated, it was found that an interconnection between these systems had been made at the shelter roof.

Remedy. The interconnection between the lightning ground system and the building ground system on the tower roof is desirable and should not be removed. This interconnection, however, should be replaced with a No. 2AWG (minimum) bare copper conductor. Brazed connections are preferable; however, bolted connections are satisfactory.

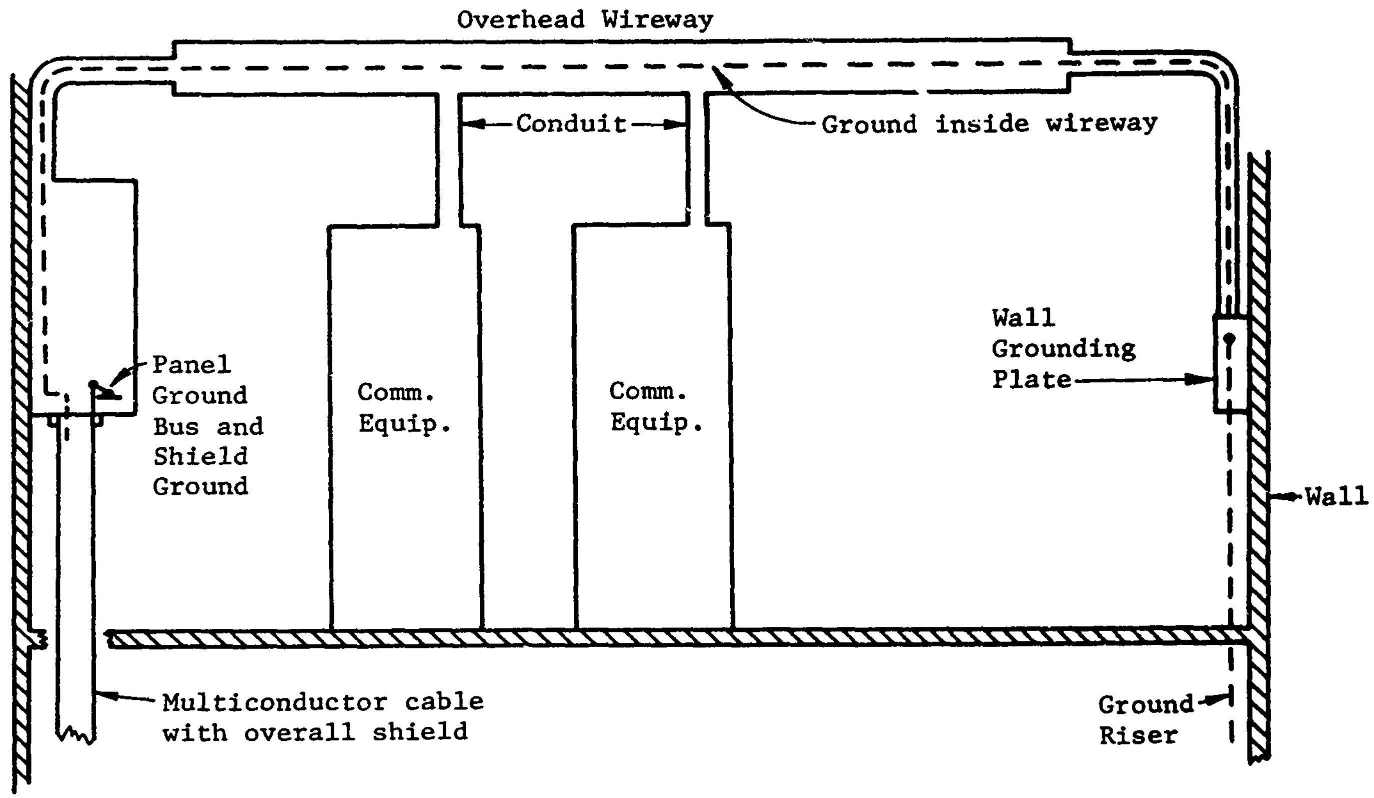


Figure 12. Grounding of equipment racks (grounding arrangement as is).

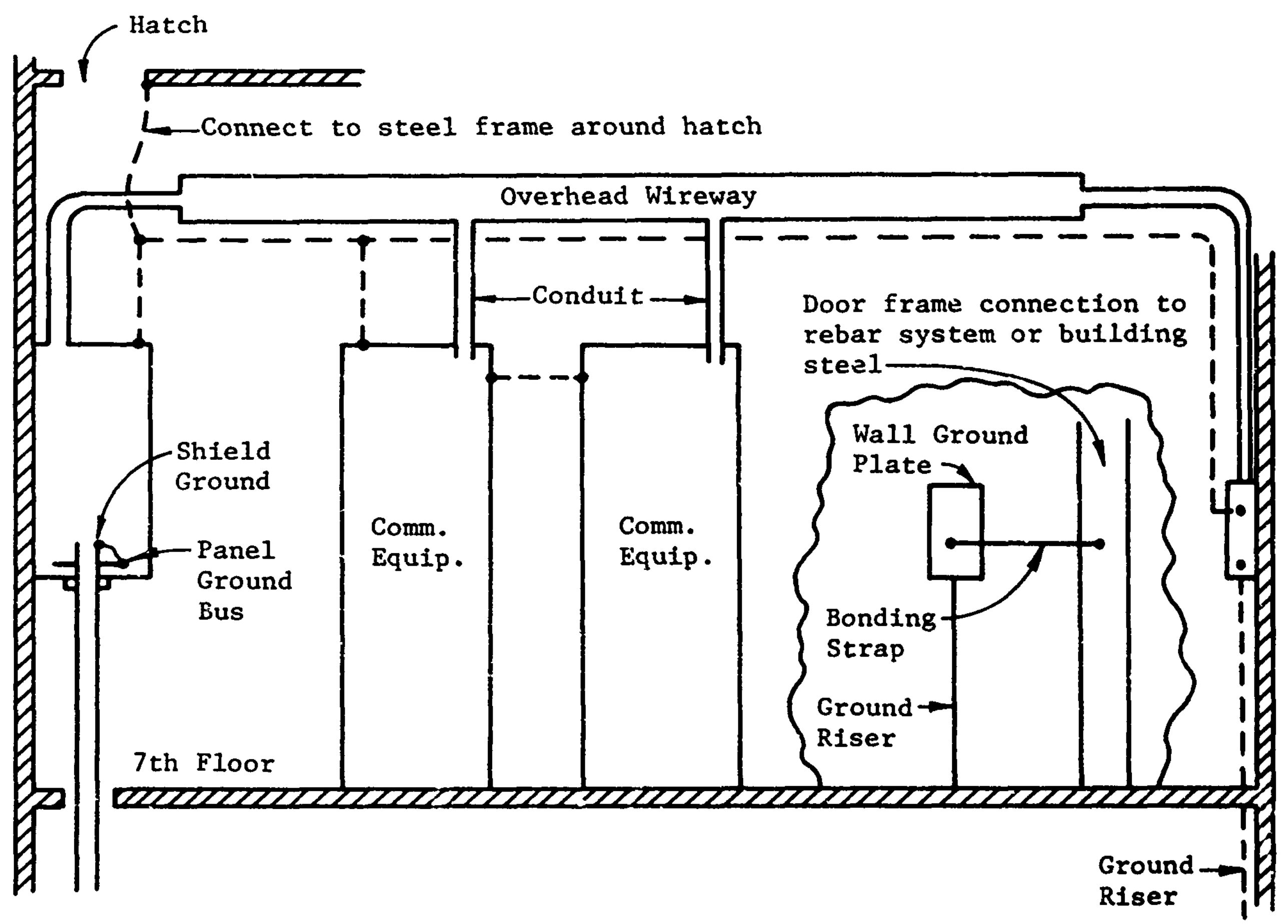


Figure 13. Grounding of equipment racks (grounding arrangement to be used).

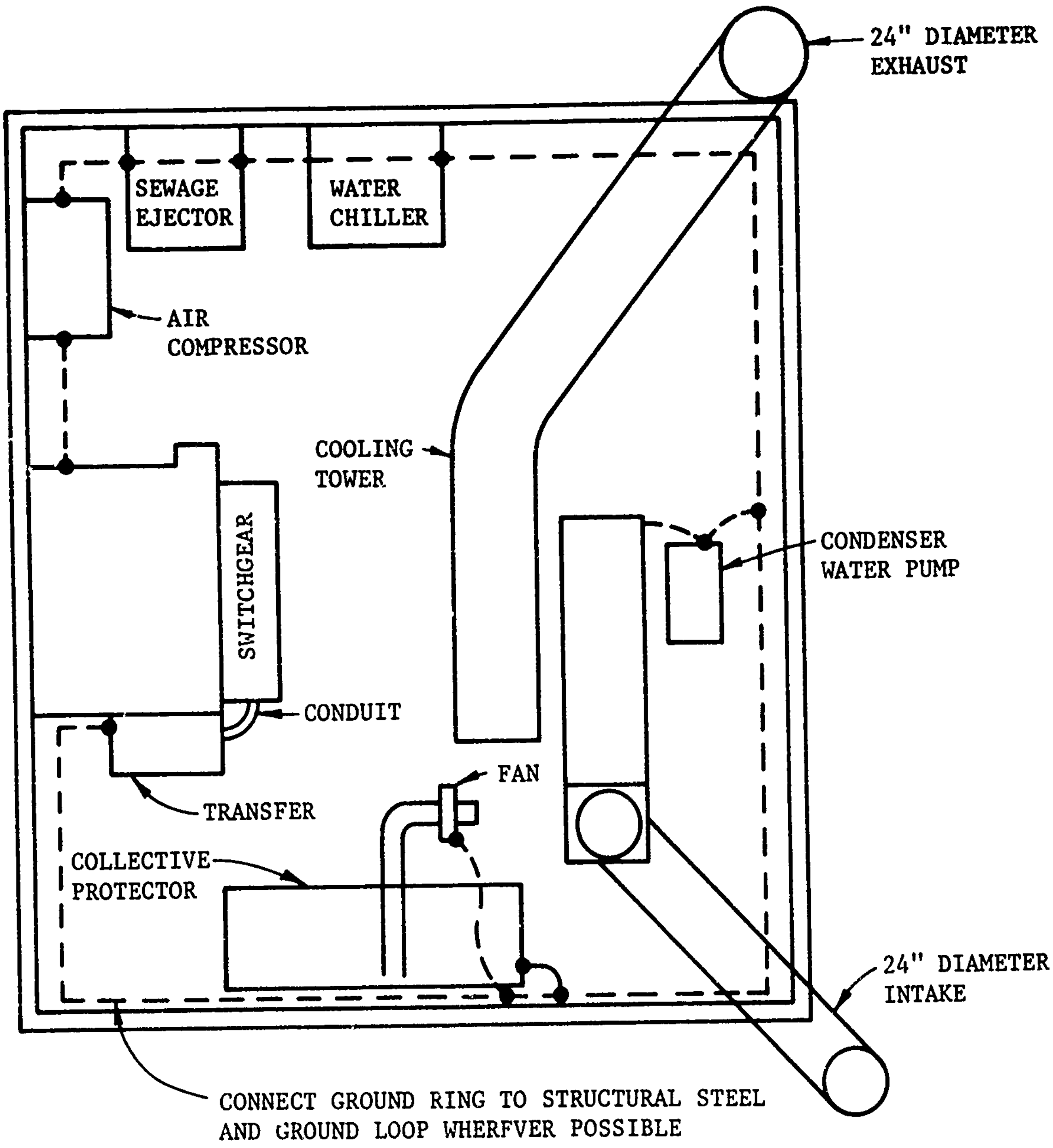


Figure 14. Grounding of electrical and mechanical equipment.

E. BONDING OF METALLIC OBJECTS ON ROOF OF SHELTER

Priority 2

Fault. On the roof there are several antennae supports and guys and a metal framework which do not appear to be bonded to any grounding system. These structures, when exposed to the threat environment, will assume relatively high voltages and will discharge to cables, conductors, electrical equipment, or other grounded objects. If the tower is struck by lightning, there will likewise be sparking between objects.

For either lightning or NEMP protection, it is desirable to distribute the surge currents over as many conductors as possible. In particular, it is desirable to carry as much of the induced current to ground as possible through the outer reinforcing steel framework of the tower.

Remedy. (1) - The ground ring around the outside of the roof which connects to the lightning rods should be connected to all of the penetrating conduits and to the eye bolts in the roof. Connections to the eye bolts should be by No. 2AWG conductors.

Remedy. (2) - The ground plane screen at the top of the roof should be connected to the lightning rod ground system and in turn connected to the reinforcing bars of the tower.

Remedy. (3) - The mounting bases of all antennas should be connected to the ground system by short, direct lengths of wire, preferable No. 2AWG.

Remedy. (4) - The metallic framework should be connected to the ground system. The grounding and bonding measures are illustrated on Figure 15.

F. UNSATISFACTORY GROUNDING IN THE SHELTER

Priority 3

Fault. There are a large number of areas where grounding and bonding should be improved. The following sections will discuss the more important recommendations. Grounding requirements discussed in other sections of this report should be considered as additions to these recommendations.

Remedy. Communications Area (See Figure 16)

1. Place a ground strap around the top of the equipment racks.

2. Connect each of the racks to the ground strap.

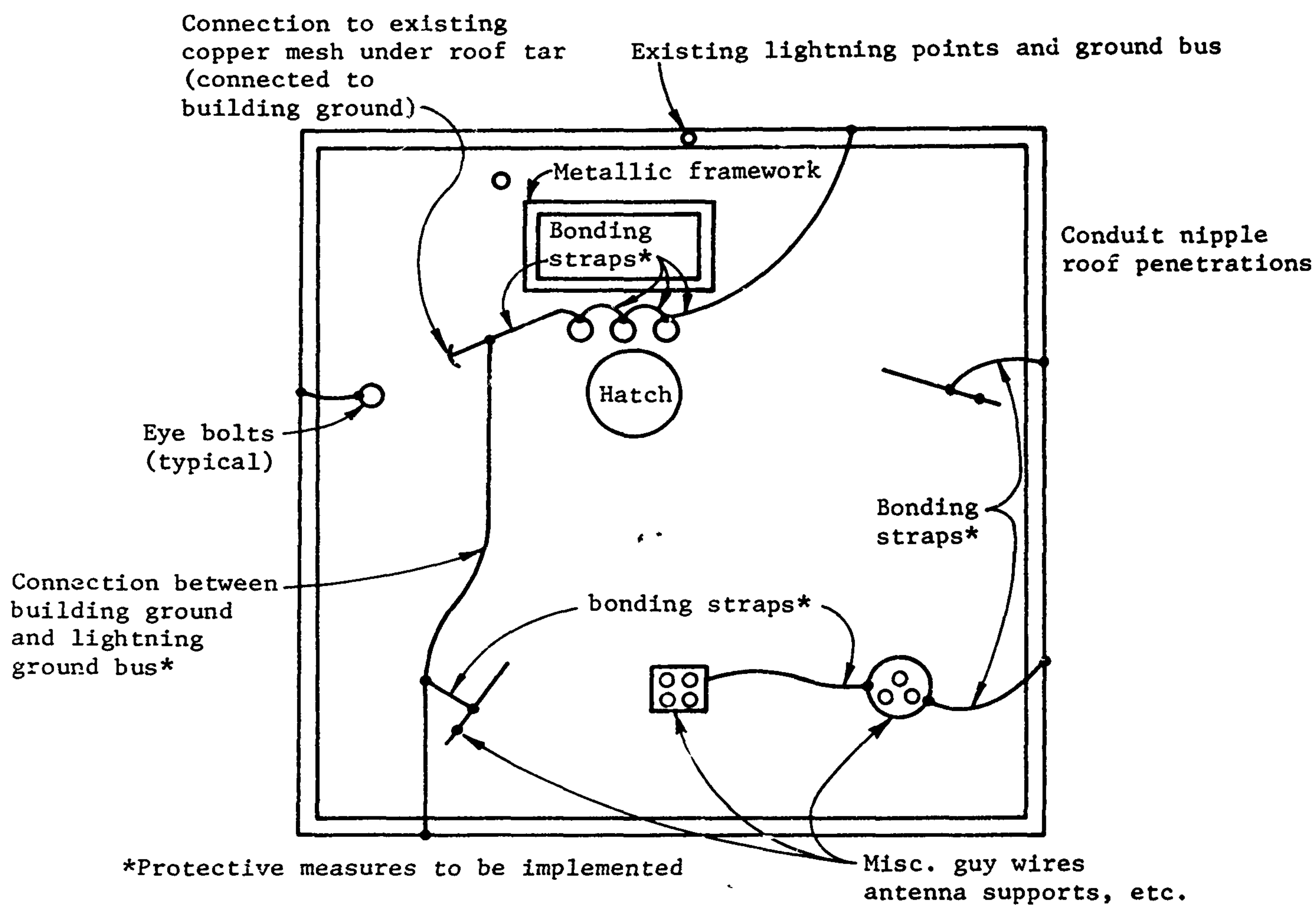
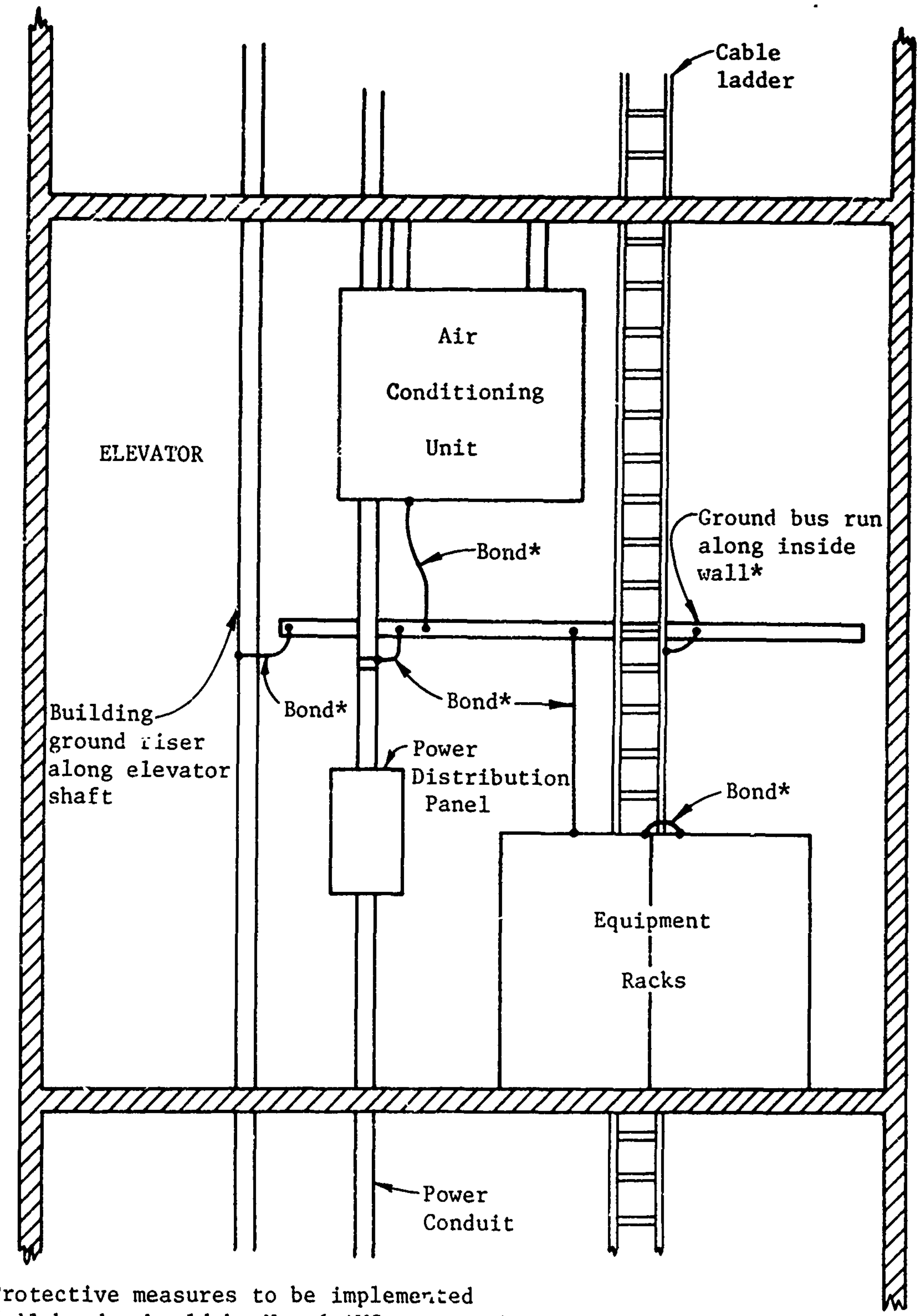


Figure 15. Interconnection of metallic objects on roof of shelter.



*Protective measures to be implemented
(all bonds should be No. 6 AWG run as short and direct as possible)

Figure 16. Bonding of equipment to internal ground ring.

3. Connect the ground strap to the building ground plate by the elevator door, using a connection of shortest length (minimum inductance) compatible with the flexibility required for shock mounting.

4. Connect any overhead cable trays to the ground strap.

5. Connect overhead cable trays to the vertical cable ladder and the steel flange around the hatch opening which are electrically connected to the metal reinforcing steel in the walls and floor.

6. Connect the fan coil unit to the ground plate by the elevator.

G. GROUNDING OF BEAM ANTENNA MASTS

Priority 2

Fault. There are two triangular antenna masts supporting rotatable beam antennas. Neither of these masts is grounded. Electric field changes from either NEMP or a lightning stroke will cause sparking and damage to electrical insulation.

Remedy. Provision should be made for interconnecting these two masts to the adjacent ground system. Interconnection should be made by a No. 2AWG or larger bare copper conductor. The connection to the ground system, if underground, should be brazed. More driven ground rods or buried counterpoise wires should be provided to lower the ground resistance at the mast. See Figure 17.

H. GROUNDING OF GUY CABLES

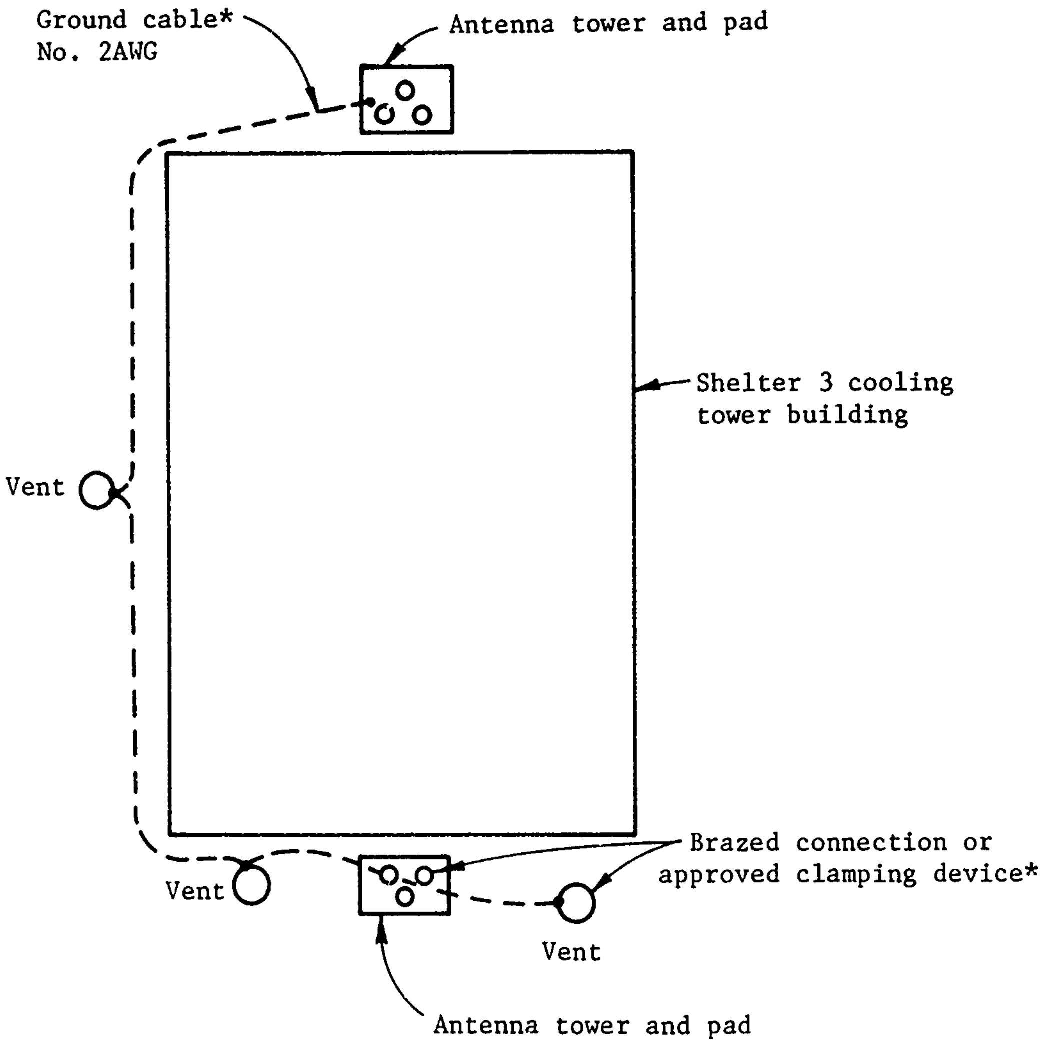
Priority 2

Fault. A lightning stroke to an antenna mast (or NEMP induced currents) could cause cracking of the concrete guy anchors, possibly even allowing the guy cable to pull loose.

Remedy. (1) - Drive a ground rod (8 feet or longer preferably) alongside each guy anchor.

Remedy. (2) - Connect each of the guy cables to the adjacent ground rod by a No. 2AWG or larger conductor.

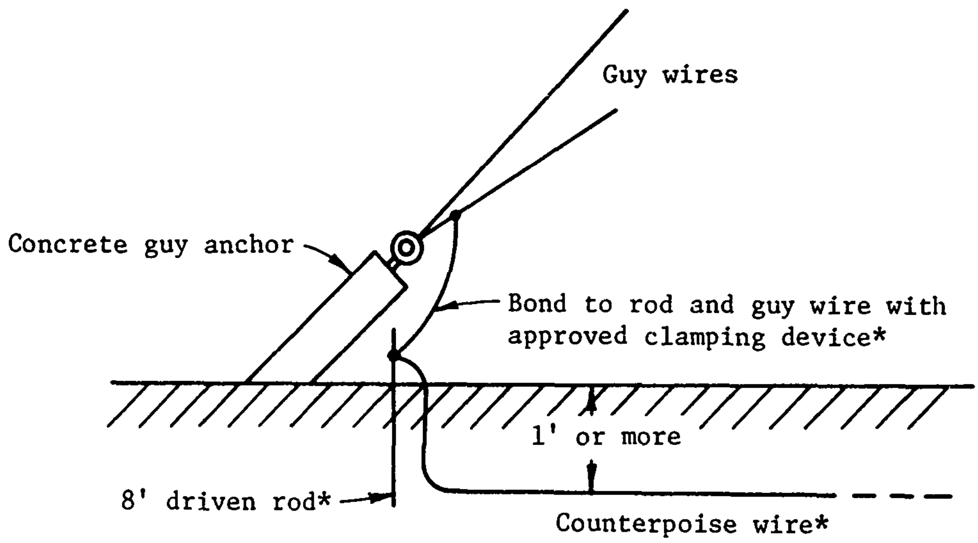
Remedy. (3) - Bond the counterpoise wire to the rod. See Figure 18.



*Protective measures to be implemented

Figure 17. Grounding of antenna masts.

At Each Guy Anchor



*Protective measures to be implemented

Figure 18. Arrangement for protection of guy anchors from lightning or NEMP.

4.0 BLAST CLOSURE VALVE ELECTRICAL SYSTEM

A. BLAST CLOSURE SYSTEM

Priority 3

Fault. Some of the wiring for the blast closure electrical system is routed in fibre duct and some in metal conduit. Therefore, the wiring can be considered to be exposed to the NEMP fields. The length of the wiring and their associated large loop areas will cause large transient voltages to be developed across components such as open relays and the solenoids which operate the swing check valves of the blast closure system.

Remedy. While it is true that components such as relays and solenoids can withstand an extremely high transient overvoltage before malfunction or failure will occur, these components in the blast closure system are classed as essential. The wiring, which is more vulnerable, is also essential. The following solution is recommended:

> Install a blast closure detector unit which actuates the trip circuits automatically for prime source protection. In addition, install Thyrectors on all swing check valve solenoids and on all blast closure trip circuits.

See Figure 19.

B. POSITION INDICATING SWITCHES FOR BLAST CLOSURE VALVES

Priority 3

Fault. Limit switches to indicate position of the blast closure valves are shielded and the wiring from the switches is carried in rigid conduit, but condulets are exposed to free field environment. Electromagnetic leakage through the cover gaskets may induce dangerous voltages on the internal wiring. This wiring runs to the A panel and may cause secondary damage there.

Remedy. (1) - Remove the condulet covers and clean the surfaces.

Remedy. (2) - Replace the original non-conductive gasket with an RFI-type gasket.

Remedy. (3) - Cover the gasket joint with a conducting weatherproof conduit (not necessary with gaskets that are impregnated with an environmental sealant).

See Figure 20.

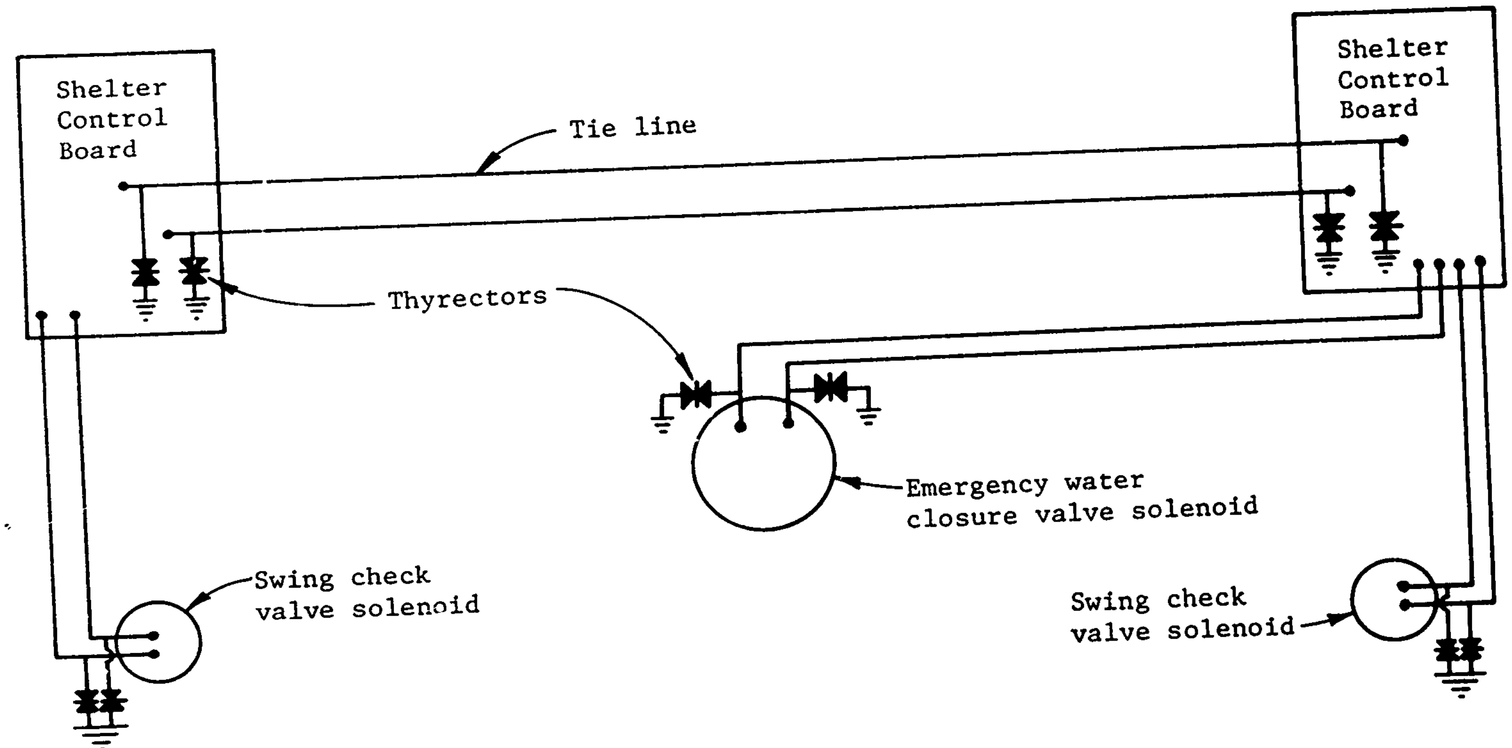


Figure 19. Typical protective device installation for blast closure system.

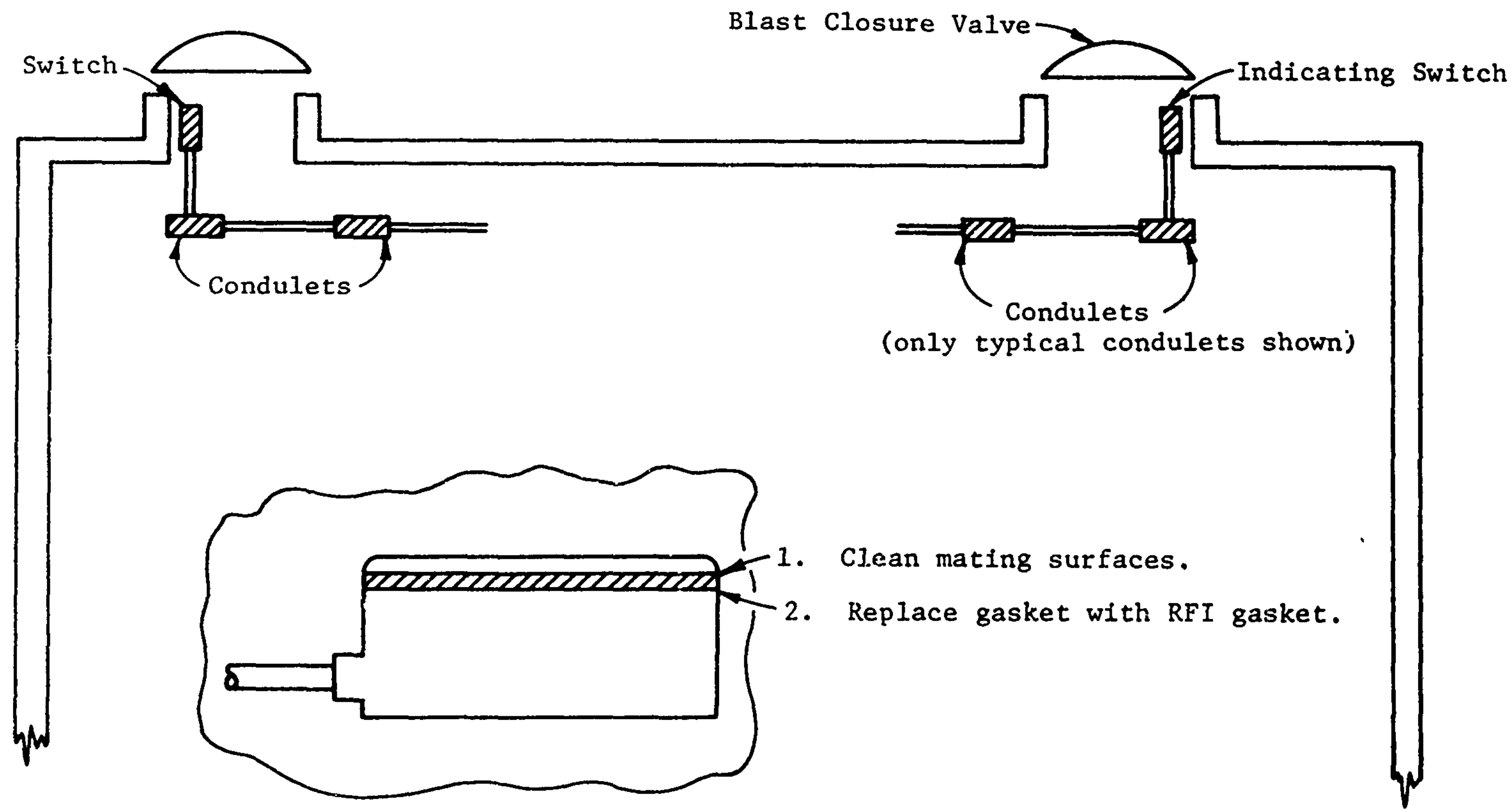


Figure 20. Treatment of condulets around blast closure valves.

5.0 NON-STRATEGIC CABLE ENTRIES

Non-strategic cable entries refers to those vault cable entries which connect to electrical or electronic equipment whose malfunction or destruction would not effect the primary mission of the shelter. The secondary effects, however, are considered in terms of the possible malfunction or destruction to equipment termed essential to the primary mission.

A. TV ANTENNA AND ROTATOR

Priority 3

Fault. The antenna for the recreational TV and its rotator is outside in the free field environment. The antenna is mounted on a plate which has been fastened to the roof of the shelter. Probably the mounting plate makes contact with the roof screen, but the connection is not visible. There is no sort of lightning arrester on the antenna lead-in nor is there any apparent lightning protection on the power cable to the rotator. The rotator power cable appears to be an unshielded lead. The feed line from the antenna is a coaxial lead. These two leads are carried through the cable trays down inside the shelter. Transient voltages induced on these leads could cause sparking to the strategic communication lines. The transient currents may couple or radiate excessively high electromagnetic fields inside the shelter. Transient voltages on the rotator lines may be coupled into the 120 volt AC distribution circuit and cause voltages elsewhere in the power system in excess of the guidelines.

These failure potentials exist in the case of a lightning stroke to or near the site as well as from NEMP.

Remedy. If not already installed:

1. The TV antenna mast should be grounded to the closest available structural ground connection.

2. If the antenna lead-in is unshielded twin lead, it should be changed to a shielded line, preferably coaxial.

3. The shield of the antenna lead should be connected to the building ground system as it penetrates the site roof.

4. A standard TV lightning arrester should be placed on the antenna lead just inside the roof. This arrester should be grounded to the building structural members. A connection to one of the metal conduit penetrations will be satisfactory.

5. The chassis of the TV set (or the shield of the coaxial cable if a balun transformer is used) should be grounded.

6. Overvoltage protective devices should be installed on the rotator power cables at the roof conduit interface. Thyrector or similar devices would be satisfactory. One device should be placed on each conductor of the cable. The ground leads from these protective devices should be connected together and grounded to the building ground system.

7. The rotator power lines and antenna lead-in wire should be contained in conduit from the entrance of the building to the top floor. If present cable ladder trays are to be replaced by RFI trays, these leads need not be placed in conduit.

8. Place Thyrectors or similar devices on the 120 volt AC power to the rotator control. These protective measures are illustrated on Figure 21.

B. COMMERCIAL TELEPHONE

Fault. The standard telephone communication wiring is routed to the shelter by overhead wire and terminates at a junction box outside the shelter. From this box the telephone wire is carried underground by fiber duct and penetrates the basement of the shelter once inside; this cable is routed to various areas.

Remedy. Telephone service protectors should be installed in the basement of the shelter at the closest possible location to the telephone cable entry and at each instrument terminal. The telephone cables within the structure should be contained in a rigid steel conduit shield and the shield containing this cable should be grounded at the entrance to the shelter.

C. BEACON LIGHTS

Fault. Beacon lights located on top of the shelter are fed from a 120/32 volt transformer which is located under the roof. Wiring from the transformer to the supervisory panel is routed in BX cable. Wiring from the transformer to the lights is exposed.

Remedy. Wiring from the supervisory panel to the transformer and from the transformer to the lights should be contained in rigid conduit or EMT. Place Thyrectors on each line-to-ground of the 120 volt power circuit, at the transformer primary. The Thyrectors should be placed within a juction box.

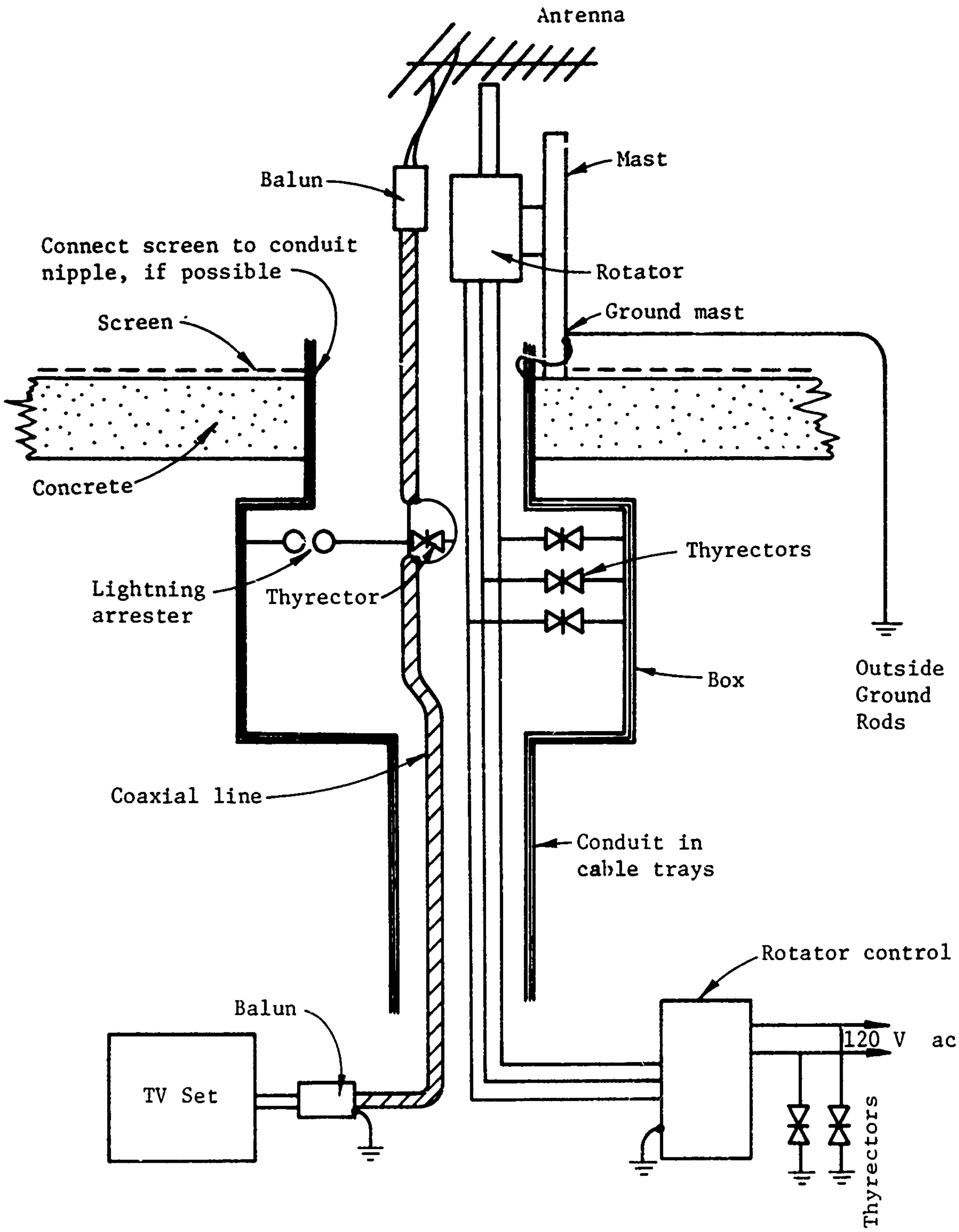


Figure 21. Protection of TV antenna and rotator.

D. TELEPHONE WIRE ROUTED ALONG COMMUNICATION CABLES

Priority 1

Fault. What appears to be a standard telephone wire has been carried alongside the communication cables up through the shelter. This wire is exposed to the electromagnetic fields within the shelter and is carried in a communication cable conduit to a telephone outside the entrance blast door. Electromagnetic fields will cause currents to flow on this wire and may couple or radiate energy to adjacent communications gear.

There is no telephone service protector at the entrance telephone that will limit surge voltages to a value not dangerous to personnel. Therefore, a priority rating of one has been applied in view of the hazard to anyone using the telephone.

Remedy. (1) - Install a distributor box and telephone service protectors on the telephone wires at the entry location (see Figure 22).

Remedy. (2) - Route the telephone wires in conduit or RFI cable trays. It can be carried in the same conduit or RFI tray recommended for the communication cables (see Figure 22).

6.0 STRATEGIC CABLE ENTRIES

A. NEMP CURRENT BROUGHT INTO SITE ON COMMUNICATION CABLES

Priority 2

Fault. High currents can be expected to be induced on the multiple pair communication cable shields. These currents, and the accompanying high voltages, will be carried into the shelter to cause damage to the internal circuits of the communication equipment. The changing electromagnetic fields associated with the flow of current can also induce dangerous voltages on adjacent electrical apparatus necessary to support strategic operation of the shelter. The problem of current flow on the cables is felt sufficiently severe to warrent a priority rating of two. The following recommendations are intended to control the pulse currents and confine them to areas where they are least likely to cause problems.

Remedy. The recommendations for protection of the incoming communication cables and the ancillary gear are shown on Figure 23.

1. Install a 2/0 copper ground bus around the inside periphery of the room containing incoming signal cables and connect it between the short sections of metal conduits feeding

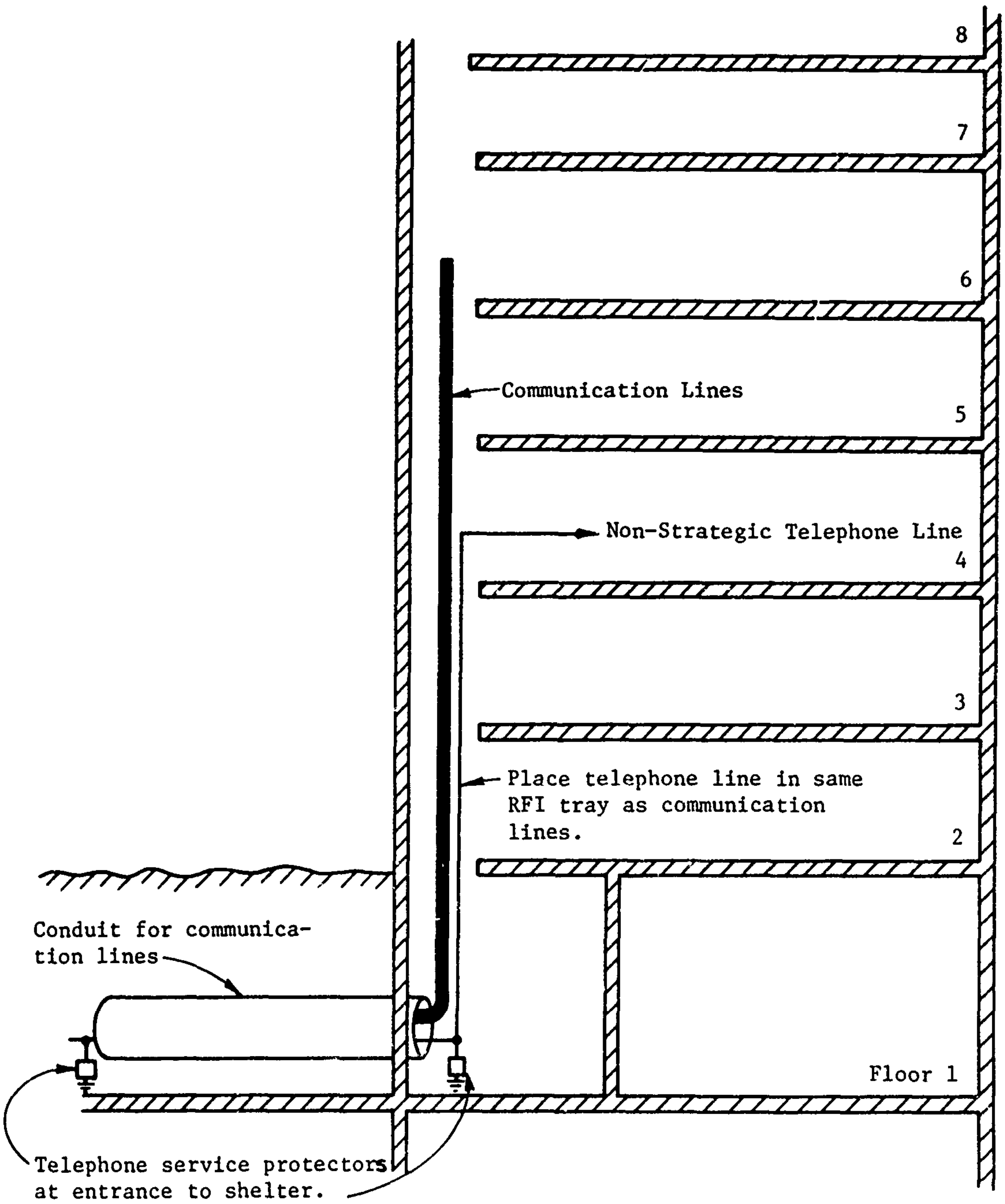


Figure 22. Telephone line alongside communication cables.

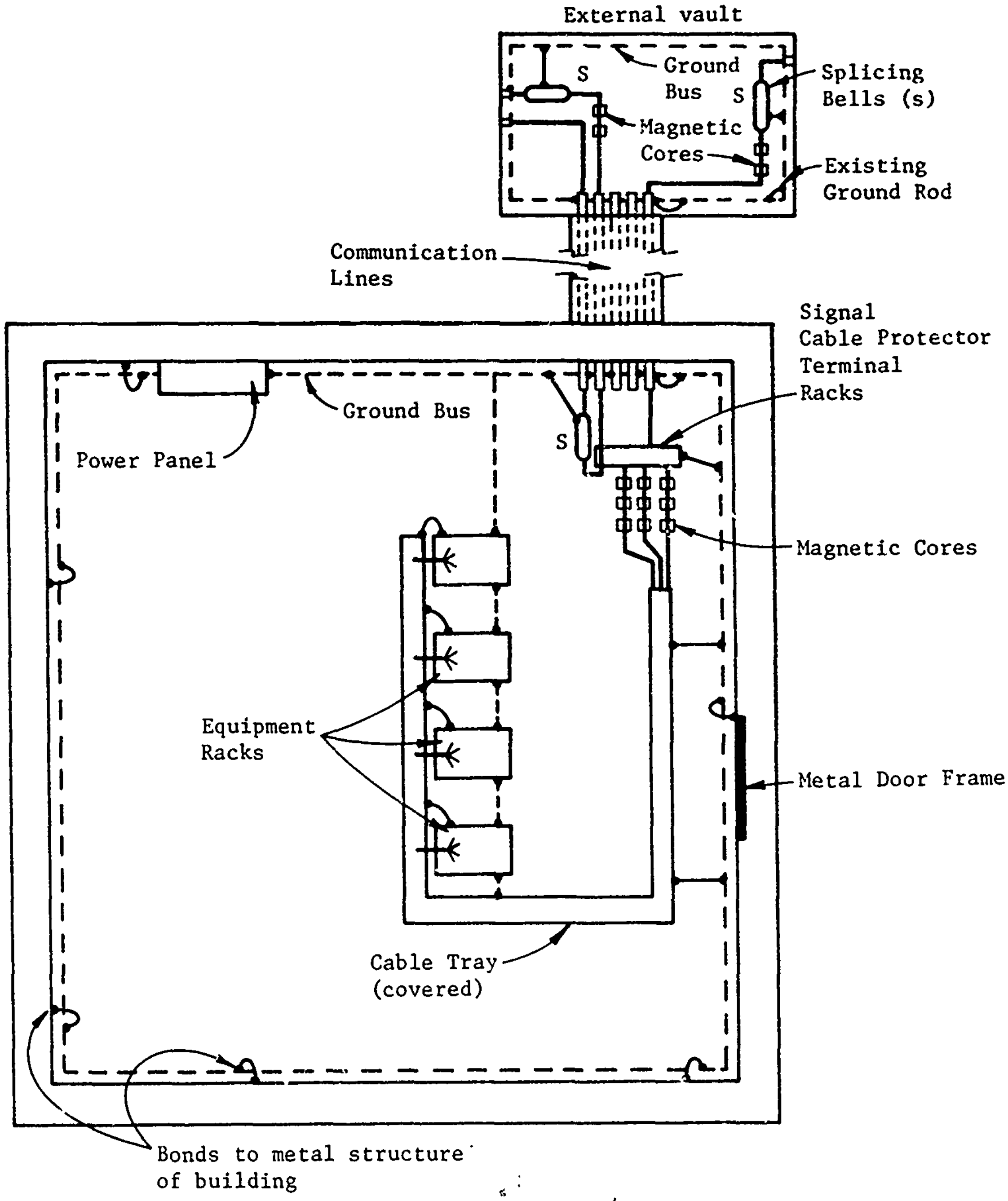


Figure 23. Grounding of incoming communication lines.

the communications cables into the shelter, and any available tie points with the steel framework available on the inside of the cable entry room. This ground should preferably be interconnected with the structural ground system in the exterior vault through which the communications cables pass prior to penetrating the shelter wall.

2. Connect the ground electrode of the protector terminal carbon blocks to the new ground system bus with as low impedance connection as possible.

3. Connect the lead splicing bells on the communications lines to the ground cable bus.

4. Connect the unused metal conduit penetrations to the ground bus.

5. Place split magnetic cores over each multiple pair communications cables inside the shelter beyond the terminal protectors towards the electronic equipment direction. These magnetic cores will induce series impedance in the communications lines to increase the effectiveness of the terminal grounding protectors and signal cable shield ground at the shelter entry location. For further information see section 14 of the Appendix.

6. Remove the long ground lead that is presently going from the communication circuits to the neutral of the power cables in the power cable connection box. This ground cable should be connected to the new ground cable.

B. ANTENNAS ON ROOF OF SHELTER

Priority 2

<u>Fault</u>. There are nine antennas on the roof of the shelter, their locations being as shown on Figure 24. Failure potentials that pertain to these antennas are as follows:

1. The antennas are the highest points on the roof, being higher than the lightning rods. Consequently, if the shelter is struck by lightning, it will be one of the antennas that is hit and not the lightning rods. The two whip antennas, Antennas #7 and #9 as shown on Figure 24, are the tallest of the antennas.

2. Antenna #9 is grounded through a jumper going over to Antenna #7 which in turn is grounded by radio leads to the

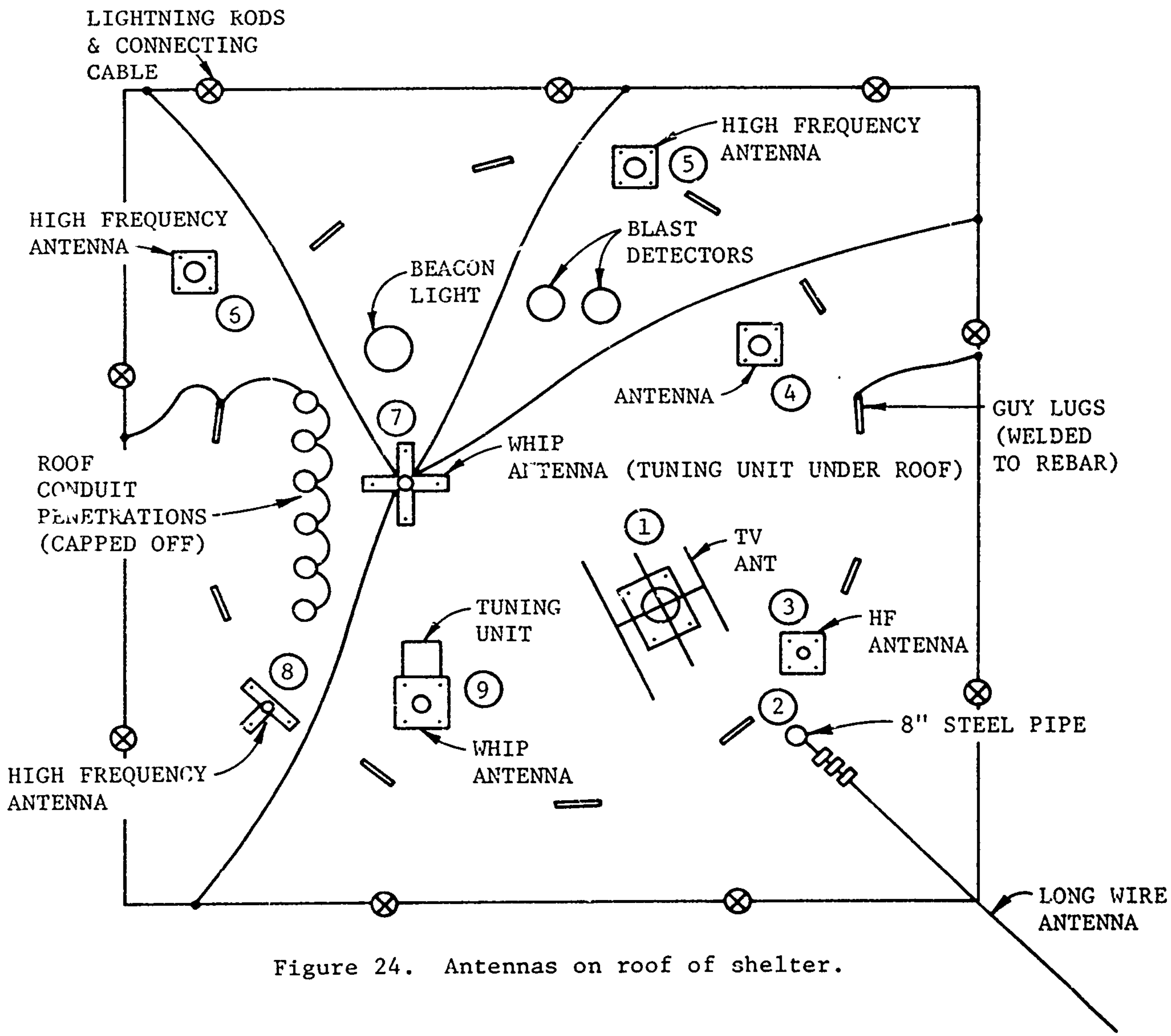


Figure 24. Antennas on roof of shelter.

lightning rod ground conductor around the periphery of the roof. Another ground lead from Antenna #7 goes down through the penetrating conduits and connects to the ground lug on the antenna tuning unit which is located on the wall just below the roof. If either Antenna #9 or #7 is struck, a portion of the lightning current will be carried directly alongside the feed lines for the other antennas and will consequently induce high voltages on those leads. Currents induced by NEMP fields will likewise induce voltages on adjacent conductors.

3. Currents induced on the antenna feed lines by the changing electric fields associated with either lightning or NEMP will be carried inside the shelter on the antenna feed lines and can there couple or radiate energy to sensitive electronic apparatus.

Remedy. (1) - Remove the ground lead that runs from the Antenna #7 tuning unit and down to the ground pad.

Remedy. (2) - Ground the supporting bases for Antennas #5, #6, #8, and #3 to the lightning ground ring around the periphery of the building.

Remedy. (3) - Connect the bases of Antennas #7, #9, #1, and #4 to the lightning ground ring. Some of these bases may already be grounded by virtue of the mounting studs, but a visible ground connection will provide positive assurance that they are grounded. The connection between the base of Antenna #7 and the lightning ground system will provide a ground for the antenna tuning unit for Antenna #7.

Remedy. (4) - Connect the penetrating conduits to the lightning ground cable.

Remedy. (5) - Connect the eye bolts on the roof to the lightning ground ring. This connection will provide the desirable interconnection between the lightning ground rod system and building ground system.

Remedy. (6) - Connect a standard communication lightning arrester to the long wire antenna with the ground electrode being connected to the lightning ground ring.

Remedy. (7) - Install standard lightning arresters on the other antennas. (These standard lightning arresters are desirable, but not mandatory.)

Remedy. (8) - Connect the shields of the feed lines to the penetrating conduits.

The above recommendations are made to minimize or eliminate the risk of electromagnetic fields caused by lightning or NEMP currents on the antenna lead-in wires or cables from interacting with sensitive electronic apparatus. Implementation of these recommendations should not imply, however, that the input circuits of receiver or the output circuits of transmitters have thereby been protected from the effects of lightning or NEMP.

C. TUNING UNITS FOR ANTENNAS #7 AND #9

Priority 2

Fault. The tuning units for these antennas are fed through unshielded power cables. The unit for Antenna #9 is the most vulnerable, but the unit for Antenna #7 is also located in a region where high NEMP fields can be expected. Voltages induced on these open wires might damage the tuning coupler.

This failure potential is assigned a priority level of two in view of the possible damage to the tuning coupler. Damage may be repairable or the coupler may be manually tuned in case of emergency.

Remedy. (1) - Enclose the power wires to the tuning couplers in conduit. If the present open cable ladder trays are replaced by RFI type trays, the wiring need not be placed in conduit also.

Remedy. (2) - The tuning couplers should be enclosed in a metallic enclosure if such an enclosure does not upset the operation of the tuning circuits.

Remedy. (3) - Thyrectors should be placed in the tuning unit between each of the control wires and ground. These protective measures are shown on Figure 25.

D. AIR GENERATOR

Priority 2

Fault. On the first floor of the shelter, there is an air generator for the pressurized communication lines. The generator cabinet has an open back and has open wire feeding it from a switchbox. The open wire length is about five feet.

The open wire is a 120 volt AC circuit. The electromagnetic field will induce a transient voltage on the 120 volt circuit which may cause damage or malfunction to strategic equipment.

Remedy. (1) - Power wiring should be carried in E.M.T. or Sealtite equivalent flexible tubing.

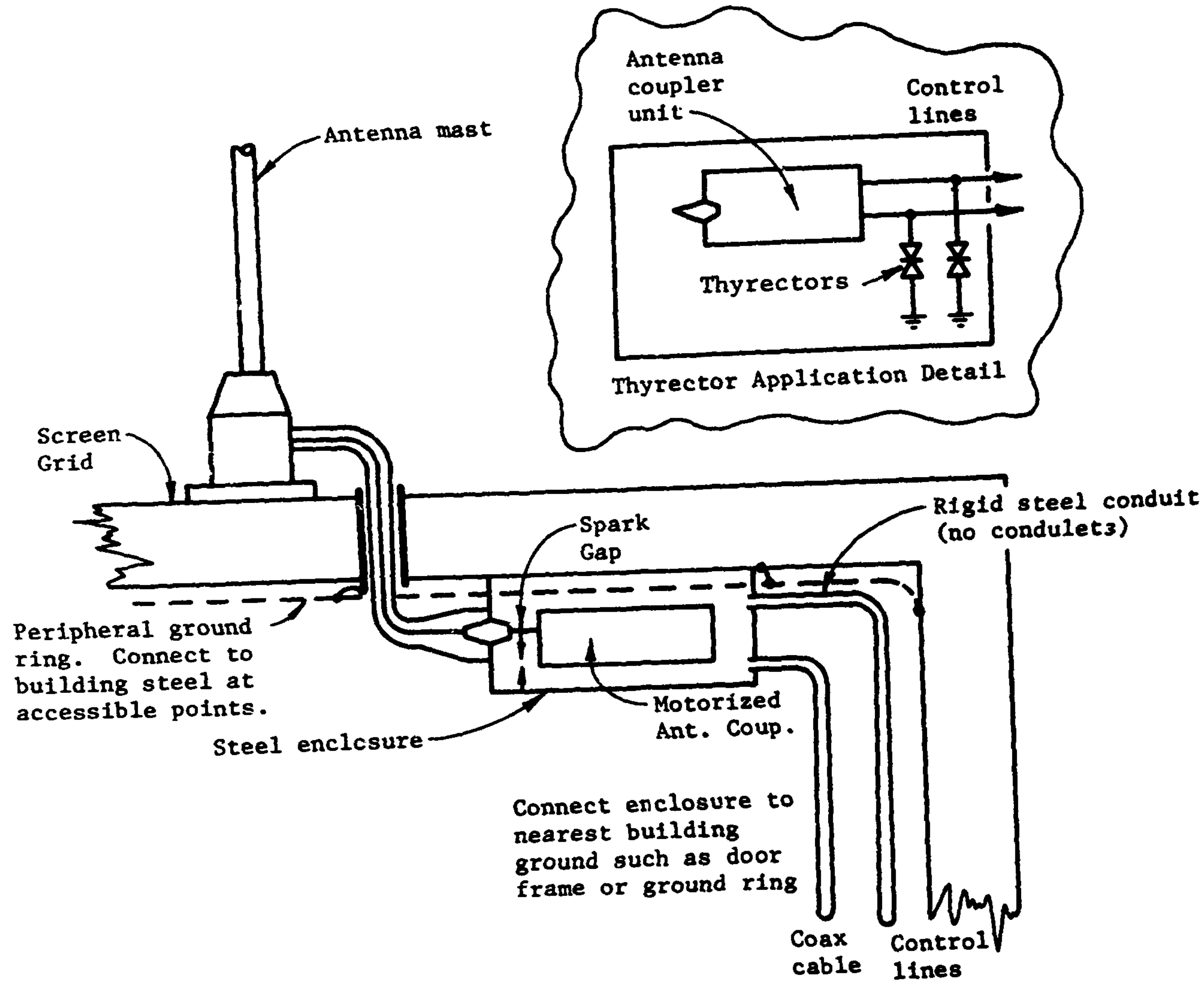


Figure 25. Treatment of antenna coupler.

Remedy. (2) - The air generator cabinet back should be fitted with metal screen to totally enclose the open wiring.

E. TERMINATION OF COMMUNICATION CABLES IN SHELTER

Priority 2

Fault. All communication cables entering the shelter terminate on standard open telephone frames. All conductors are provided with standard telephone-type carbon block protectors. The shields of these incoming communications cables (spiral-wrap aluminum) are intentionally not grounded at the frames.

Remedy. At the frames, all cables with shields should have these shields grounded to the ground bus which is already installed along the top of the carbon block frame. Also, the ground bus should be connected to the framework itself. See Figure 26.

7.0 ENVIRONMENTAL CONTROL

The environment control system is the mechanical plumbing and electrical system which provides air conditioning for the shelter. This includes the wiring, fans, pumps, and plenums.

Air conditioning is provided for the various floors of the shelter. The heat exchanger is located in the basement.

A. MOTORS OF ALL FANS AND PUMPS

Priority 3

Fault. While the motors are adequately enclosed, the power to them is carried in BX cables of lengths usually on the order of two to three feet. H-fields internal to the shelter system may induce voltages on the wiring exceeding the transient overvoltage guidelines.

Remedy. (1) - If the length of BX cable is two feet or less, accept the risk.

Remedy. (2) - If the length of BX is greater than two feet, connect a No. 6AWG copper wire in parallel with the BX cable and connect it to ground the metal condulet box and the motor frame. See Figure 27.

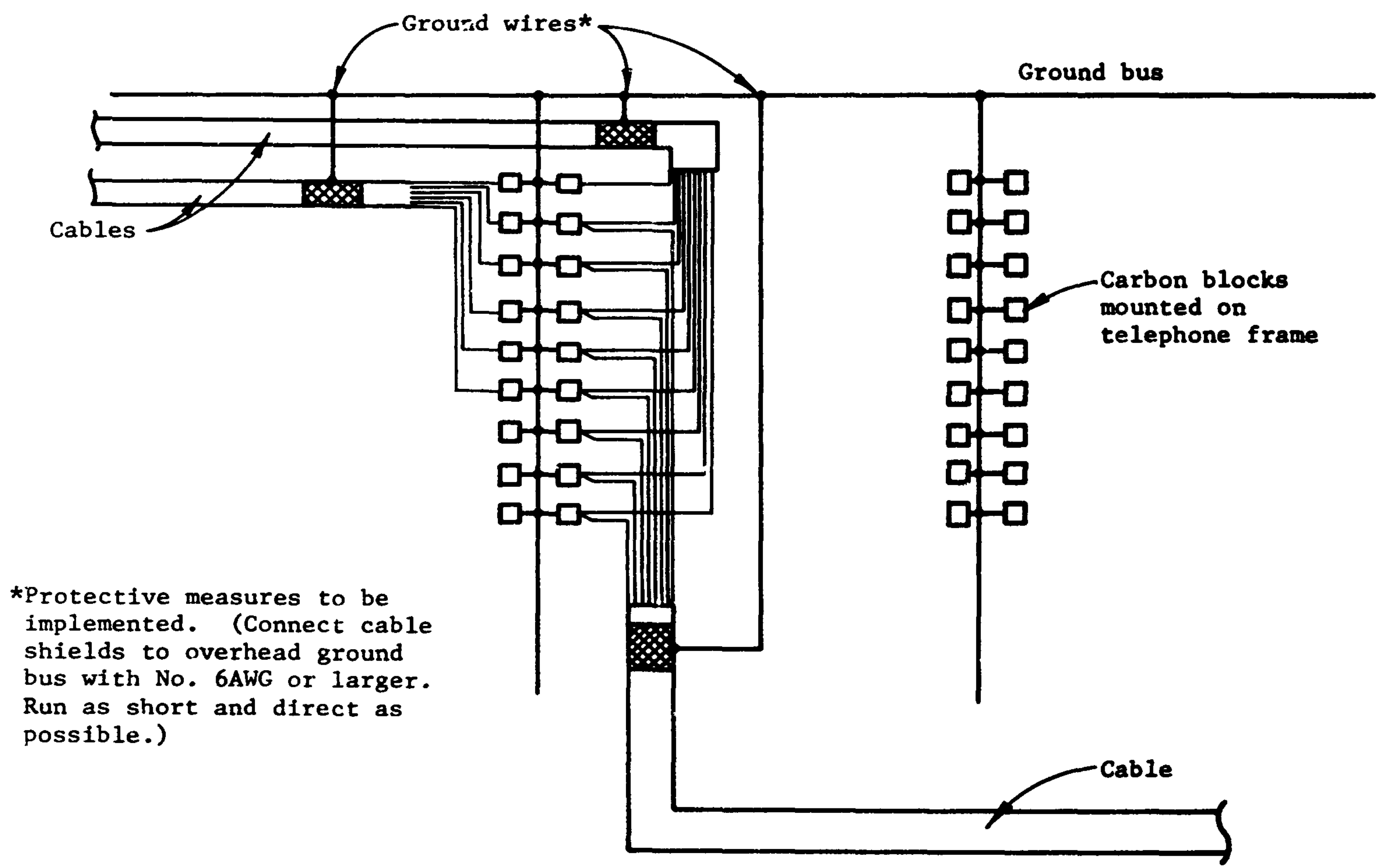


Figure 26. Termination of communication cables in Shelter 3 frame room.

1. If BX is greater than two feet:

   A. Connect No. 6AWG wire between condulet and motor connection box.

   B. Tape wire alongside BX.

2. If BX is less than two feet, no wire necessary.

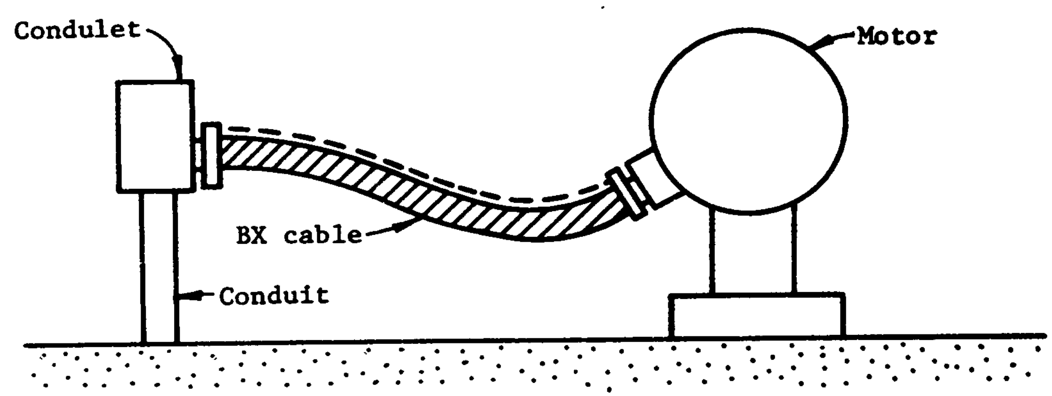


Figure 27. Treatment of BX cables to motors.

B. FLEXIBLE JOINTS IN AIR-HANDLING DUCTWORK

Priority 3

Fault. On both the cooling tower and the collective protector, there are flexible insulated joints in the air-handling ductwork. Rapidly changing H-fields can induce high voltages around loops and cause sparking across these joints. Sparking may not be harmful, but if previous damage had caused any accumulation of flammable vapors, the spark might set off a fire.

Remedy. Connect a flexible ground strap across the joints. This strap may be copper braid, 0.25" or wider, and a length preferably not exceeding six inches. Places where joints were noticed and jumpers should be added include, but are not restricted to, the following:

1. intake air plenum to collective protector;

2. exhaust air plenum to collective protector;

3. intake air plenum of cooling tower;

4. exhaust air plenum of cooling tower;

5. exhaust air duct from radiator of diesel generator.

See Figure 9.

8.0 ELEVATOR

The elevator traverses the various floors of the shelter. The elevator control panel is located on the first floor adjacent to the elevator shaft. This section will consider the failure potentials of the elevator electrical system.

A. ELEVATOR POWER

Priority 3

Fault. Control and lighting power for the elevator is through unshielded PVC cable. The cables form a large open loop. Rapidly changing electromagnetic fields within the shelter will induce high voltages on these conductors to ground. These voltages may:

a. damage the power circuits of the elevator, thus rendering the elevator inoperative, and,

b. inject high voltages into the power distribution system with consequent risk of damage to other equipment.

Remedy. (1) - Feed the elevator motor through an isolation transformer having an electrostatic shield between windings. The isolation transformer should be rated 208V/208V and connected delta-wye. Placing the transformer adjacent to the elevator would simplify problems related to switchgear and feed lines. This affords isolation between the elevator power and the communication power and would be an improvement over the presently installed system, since a surge induced on the elevator power would have to pass through one transformer to get to the communication gear.

Remedy. (2) - Install Thyrectors between each line and ground on the secondary of the isolation transformer.

These recommendations are illustrated on Figure 28.

Remedy. (3) - Install Thyrectors at the traction motor terminals and at the terminals of the brake circuit.

Remedy. (4) - Install Thyrectors on the elevator control circuit. These Thyrectors could be installed at the junction box to which this circuit runs.

B. ELEVATOR CONTROL

Priority 3

Fault. While the call button and floor leveling circuits are carried in conduit and are well protected, they terminate in the elevator control panel which, because of its construction, offers little shielding to the components inside. The control lines going to the elevator cab are completely unshielded and form a large loop. High surge voltages can thus be induced on the elevator control circuits.

The elevator controls are mostly relays and are not inherently sensitive to transient overvoltages. Most likely, transient overvoltages would only cause flashover of the wiring. Depending on the circuit voltage, the flashover may cause a subsequent power arc and cause the fuses feeding power to the control circuit to blow. Presumably, the fuses could then be replaced and the elevator placed back in operation.

There exists, however, the possibility that damage to the control circuits might be more extensive than a blown fuse. Specifically, the control circuits might be inoperative even though the protective measures recommendations in section 8.A. had prevented damage to the elevator traction motor.

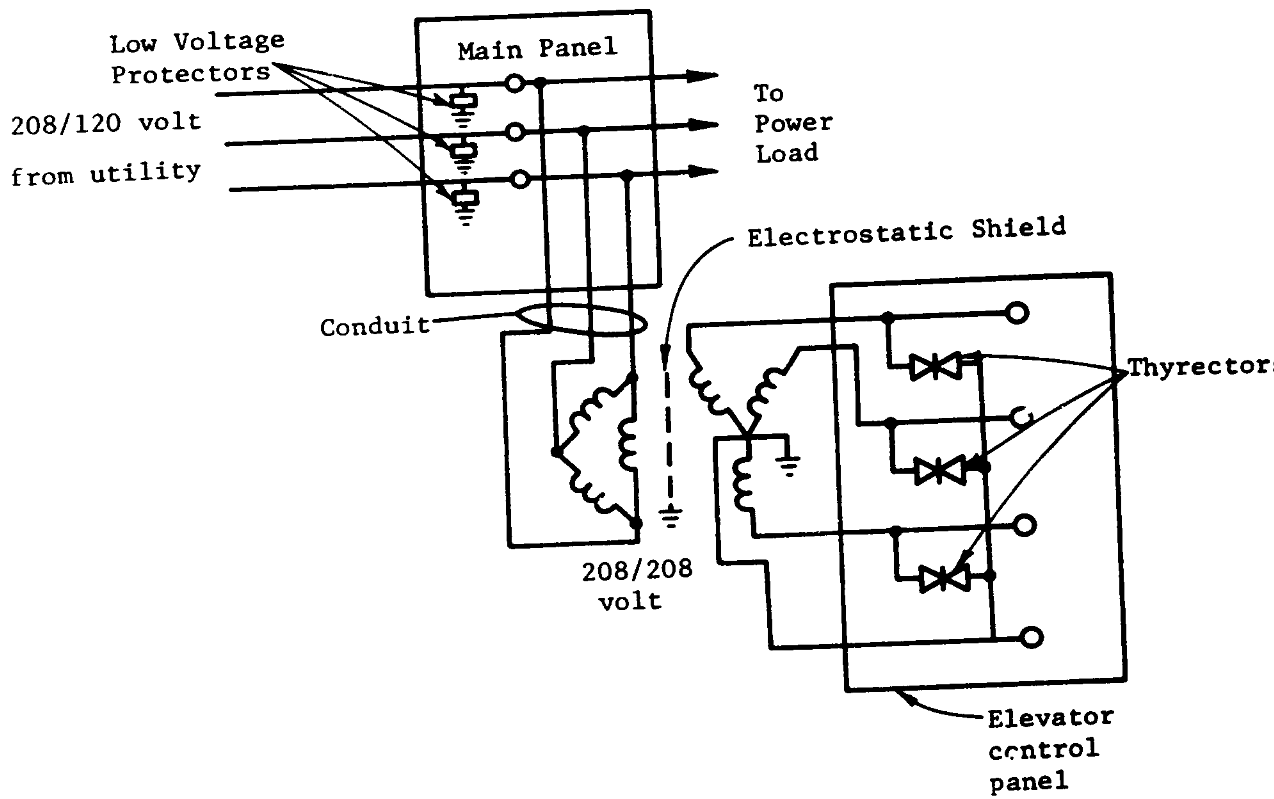


Figure 28. Surge protection for the elevator power.

Remedy. Install a separate shielded control system as a backup, one that permits manual control of the elevator even if the automatic control circuit is inoperative. This circuit would control only the elevator motor and brake.

The elements of the system are shown on Figure 29. Additions to the present system would be:

1. An emergency control switch in the elevator cab. (A second control switch could be provided on the first floor.)

2. A new shielded drop lead from the elevator cab.

3. A manual changeover switch to provide direct control of the motor and brake contactors.

This emergency control system would be de-energized and shielded and, hence, not vulnerable to transient overvoltages. Use of a manual changeover switch would eliminate most problems of interlocking two separate control circuits since only one would be operative at a time. The changeover switch could be sealed with a wire and lead seal to discourage indiscriminate usage of the emergency system.

9.0 CONCLUSIONS

1. This study describes considerable retrofit measures for existing shelters which have no existing NEMP hardening measures completed as a result of the additional grounding, bonding, and interconnection electrically of the structural reinforcing steel, metal piping, conduit, trays, grounding wires and cables. The overall effect is to greatly increase the shielding effectiveness of the shelter resulting in considerable reduction of induced electric and magnetic fields within the shelter and for the protection of sensitive electronic systems contained in the shelter.

2. The installation of voltage limiting and protector devices and the additional shielding and shield grounding of power conductors and control wiring to the extent called for in this study should eliminate any of the destructive hazards of arc-over and sensitive equipment component destruction resulting from voltage surges conducted to electrical or electronic equipments.

3. The majority of all NEMP hardening measures described in this report are of a type that would have been included in the initial design of a shelter where NEMP hardening protection was desired. Further and stricter hardening measures would normally be in addition to measures described

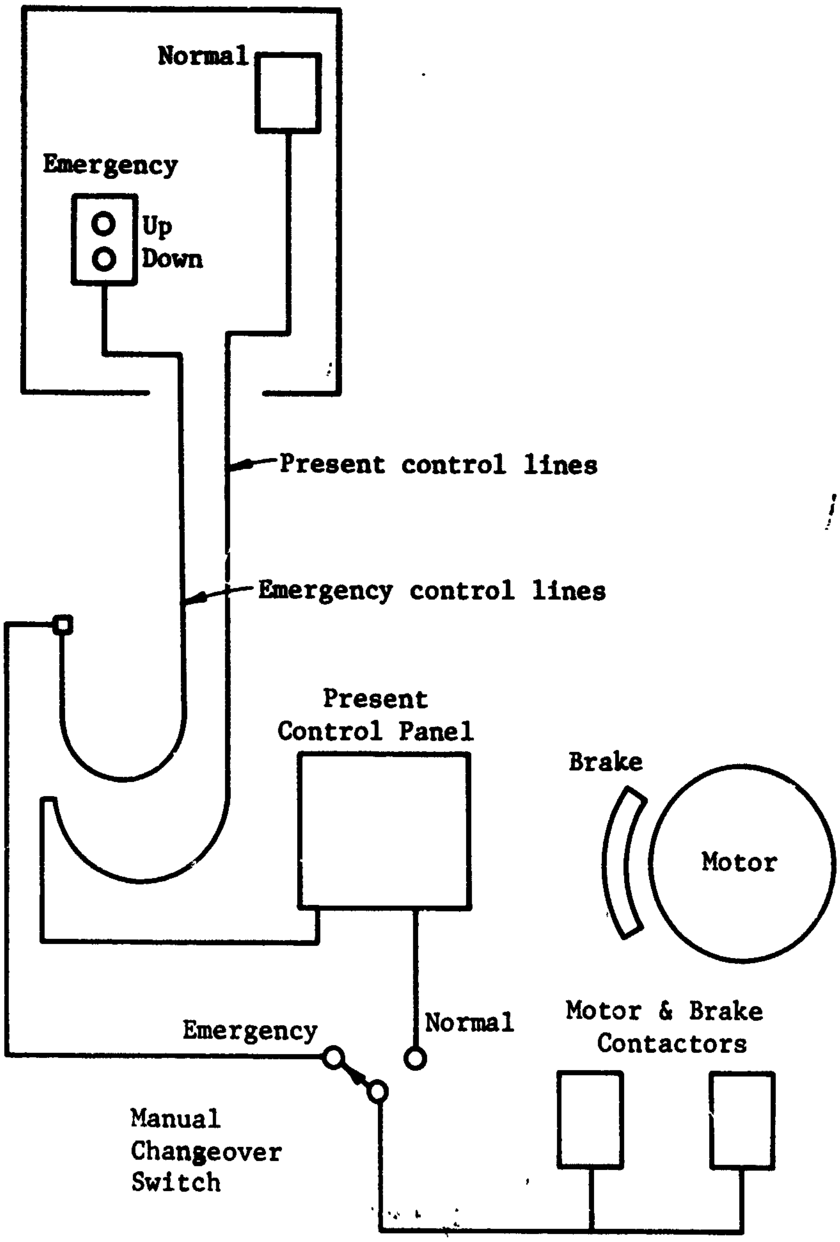


Figure 29. Emergency control system for elevator.

rather than in place of them. For example, if the shelter was basically an electromagnetic shielded enclosure, the treatment called for on penetrating signal lines, pipes, and power conductors would be similar to those described in this report; and only a portion of the additional bonding of grounding buses, rebar, and grounding system connections would be pre-empted.

Appendix

NUCLEAR ELECTROMAGNETIC PULSE EFFECTS
DESIGN PARAMETERS FOR PROTECTIVE SHELTERS

A-1.0 PURPOSE

The purpose of this appendix is to provide pertinent engineering data for the design of protection for critical installations against the harmful effects of the electromagnetic energy produced as a result of a nuclear explosion (NEMP hardening).

The nuclear electromagnetic pulse (NEMP) will produce two general catégories of effects which can result in faulty operation of electrical/electronic apparatus, permanent damage to particular kinds of components and cables and, in some cases, pose a serious shock hazard to personnel. First, radiated (or induced) electromagnetic fields are produced which are best reduced at an installation by proper metal shielding. Second, the fields produced can induce large conducted surge currents on power, telephone, and other lines and metal conductors entering the installation. These surge currents can, in many cases, be suppressed by judicious application of voltage and current limiting devices in lines which are capable of carrying these currents into a critical installation.

This appendix will be concerned with protective measures against these two general NEMP effects, including proper bonding and shielding of installations, and correct methods of placement of various protection devices. The application of these protective measures will not be restricted to the design of new installations, but may also be applied to existing installations on a limited basis.

A-2.0 THE INCORPORATION OF NEMP PROTECTION IN CONSTRUCTION PLANNING

Those concerned with the construction of new facilities requiring NEMP protection will need to consider a number of sections of this appendix, depending upon the degree of hardening against NEMP required.

This appendix will divide the NEMP environment into three general environmental threat levels considered as damaging to a structure which must continue functioning after one (or a multiplicity) of high energy NEMP threats occur. The EXTREME case will represent the highest level of electric and magnetic field strength that is anticipated from any potential NEMP environment. SEVERE and MODERATE constitute two lesser subdivisions of the threat levels which can occur for which it will be desirable to design protective measures to enable facilities to survive and continue to operate under these conditions. The range of electric and magnetic field strengths for the three subdivisions EXTREME, SEVERE, and MODERATE are given in the classified addendum of reference 1 as well as a description of the corresponding frequency-energy spectrum anticipated.

Construction of facilities designed to meet the EXTREME case will need to make use of virtually all of the available protective measures known within the "State-of-the-Art" including the best magnetic and electric field shielding available which must start with an all-welded steel enclosure. The SEVERE and MODERATE cases as considered in this appendix will require protection as indicated in Table A-1. This table points out pertinent sections of the Technical Note which will require attention for the particular threat level under consideration.

A-3.0 APPLICATION OF NEMP TECHNIQUES TO EXISTING STRUCTURES (NEMP RETROFIT)

A-3.1 Planning

Where costs are not prohibitive it will be desirable to apply NEMP protective measures to existing communications facilities, personnel shelters, or otherwise nuclear hardened buildings. Many present structures were built before the existence of an NEMP threat had been realized. In the design of protective measures for such a large variety of structures, consideration of the following items should be very important to the designer providing NEMP hardening for the structure:

A-3.1.1 Threat Levels

The expected NEMP threat levels at the structure are based on type of burst, distance to burst, and weapon yield. A guideline as to weapon yield and anticipated distance from a burst would be the overpressures that the building has been designed to withstand.[1,2,22]

A-3.1.2 Susceptibility

A limited amount of susceptibility data is given in existing NEMP handbooks and test reports. Very little is available from equipment manufacturers. In general, only engineering estimates of system susceptibilities are known at this time. Some components of systems are known to be more susceptible than others based on inherent voltage and current characteristics. Discussion of general susceptibilities of some types of components which are common to a large number of systems are given in section 6 of this appendix. Power susceptibility of some components such as motors, relays, transformers or switches have been measured.[3,5]

A-3.1.3 Cost of Retrofits

The level of funding available as compared to the cost of the anticipated protective measures may predominate in the determination of the extent of the NEMP retrofit program. In some cases, it may be more economical to abandon a site and rebuild with plans which include design of protective measures.

TABLE A-1

Protection required for severe and moderate NEMP levels.

ITEM	SEVERE	MODERATE
1. Primary Distribution System	4.1	4.1
2. Secondary Distribution System	4.2	-
3. Antennas	4.3	4.3
4. Surge Protection Devices	5.1, 5.2, 5.3	5.1
5. Grounding	7.2, 11.0, 11.1	7.2, 11.1
6. Safety	8.2	8.1
7. Shielding	10.2, 10.4	10.3, 10.31, 10.32
8. Other Penetrations	12.1, 12.2, 12.3	12.1, 12.2
9. Filters	5.5, 5.5.1	5.5.1
10. Signal Lines	5.4	5.4
11. Lossy Line	5.8	-
12. Special Equipment Protective Requirements	6.2	-

A-3.2 Examination of Plans

A preliminary step in the program to NEMP harden existing facilities is to examine available construction drawings and make a determination of the construction methods used at the site. For example, if the construction is typically reinforced concrete, determine the diameter, spacing or extent of use of rebar and if any portion of the rebar was welded or brazed at joints and intersections. A limited amount of shielding from radiated fields will be provided by having bonded reinforcing steel as part of the basic structure.

A-3.3 Site Survey

After an initial examination of construction drawings and plans it will be advisable to make a visual inspection of the facility; compare construction to as-built drawings if available.

A-3.3.1 Shielding

Any continuous steel plates will also provide shielding and should be considered as part of the NEMP protection inherent in the structure (see section A-10.3). The use of additional shielding such as form fitted copper sheeting, welded steel lining, or built in place commercial shielded enclosures should also be considered (see section A-10.4).

A-3.3.2 Grounding

The determination of the availability and quality of the grounding system for impulses and surges would be the next step in a retrofit program. Existence of ground connections to the basic structural steel and reinforcement steel should be determined through resistence measurements (see sections A-11.2 and A-7.2). These grounds can be supplemented by adding an appropriately designed impulse ground counterpoise system in order to obtain surge grounds with resistances on the order of about ten ohms (see section A-11.0). Measurement of soil resistivity will aid in designing additional grounding.

A-3.3.3 Commercial Utility Lines

It is usually anticipated that commercial utility lines will be destroyed and so a transfer switch will normally be available to switch the load to the emergency power system. This transfer switch must be protected from damage from the initial NEMP encountered and a standard lightning arrester at the transfer switch is normally sufficient for this purpose if connection to a low impulse impedance ground is available near the transfer switch and the switch is on the high voltage side of a step down transformer. Typically, the nearest existing lightning arrester will be on the last overhead transmission line pole. The site survey should locate and evaluate the quality of existing arresters, potential transfer switch grounds and distribution transformers.

A-3.3.4 Emergency Power

Vulnerable points of the emergency power system which require protective measures should be determined during the survey. These include remote control conductors, remote indicator wiring, generator exciter control, and battery charging circuits. All such conductors should be contained in ferrous conduit with threaded couplings. Power distribution from the generator must be similarly contained in ferrous conduits. Entries of this conduit into switches and junction boxes near the generator should be suited for application of radio frequency gaskets or electrically conductive bonds.

A-3.3.5 Internal Power and Control Wiring

The means of distribution of power conductors and control conductors within the facility should be determined by examination of the construction drawings and visual inspection of the installation. The type of conduit used is important. Rigid ferrous conduit with threaded couplings can provide a sufficient shielding of conductors contained therein for EXTREME threats. Thin wall conduit with condulets gives considerably less protection and will require additional measures, such as the application of conductive, silver loaded plastic resins.

Numerous bends in conduit runs tend to degrade the shielding provided. The larger the conduit diameter the more effective it will be.

Multiple runs of conductors within cable trays tend to provide limited shielding for each other. In the survey, such multiple cable runs should be examined for the possibility of installing them within enclosed ferrous raceways.

Entries of conduit into switch boxes and junction boxes, should be inspected for continuity, tightness and quality of couplings. Box lids will require installation of radio frequency gaskets with appropriate treatment of the mating flanges with conductive coatings.

Open indicator panels and control racks may require enclosure of wiring within an integral metal cabinet, and the results of the survey should indicate the quality of existing panels, openings, and seals, as well as existing potential for added shielding measures.

A-3.3.6 Signal and Telephone Lines

Overvoltage protection measures should be applied at the point where the lines first penetrate the shelter wall. (section A-5.4) All incoming lines (this includes power, telephone and data lines) should be rerouted so that at the entry point, protectors can be physically mounted on a bulkhead which, in turn, can be electrically connected directly as possible to an impulse grounding system (section A-11.1).

A-3.3.7 Antenna Lead-in Cables

Antenna masts and cables should be examined for the existence of previously installed lightning arresters and grounds. The penetrations

of antenna lead-ins into the structure should have the type of protection indicated in Figure A-1 and discussed in section A-4.3.

A-4.0 STANDARD EXTERNAL PROTECTION

A-4.1 Primary Power Distribution Arresters

The most common primary power distribution lines operate in the range of 2.4 to 7.2 KV line-to-neutral or 4.16 to 12.5 KV rms line-to-nominal voltages. Because of efficiency and other considerations, most primary distribution is wye-connected 4-wire service with a grounded neutral. Lightning arresters are generally connected from each phase to ground at locations such as transformer banks, and enclosed switches and line terminations. To minimize interruptions by lightning surges, the most common type of arrester on primary distribution lines is the valve-type. This type interrupts the power-follow arc at the first zero-voltage crossing after the surge. Primary distribution arresters are placed as near as possible to transformers and substations to provide maximum protection to the apparatus connected to the line. Other arresters may be located at periodic intervals on the line to protect insulators, preferably at points where the line tends to flash over easily such as at discrete changes in direction. The typical primary arrester will fire at about three to four times normal peak voltage within a few microseconds and will discharge 50,000 amperes or more for a few milliseconds with 200-300 volts drop across the arrester. These arresters will give normal protection from lightning surges and will also provide some protection from an NEMP pulse induced on the power line.

A-4.2 Secondary Power Distribution Arresters

"Secondary Type Arrester" is a standard ASA classification. Secondary distribution voltages normally range from 120 to 440 volts rms (root mean square), with numerous variations of single-phase and three-phase service. Some services do not use a neutral wire or a ground wire (three-phase Delta connection).

The voltage rating of an arrester is the maximum rms voltage-to-ground at which it will interrupt follow current. This rating is not the sparkover potential as in the case of protectors. The "impulse sparkover potential" of an arrester is a separate value based upon a nominal 1-1/2 x 40 microsecond test wave and may be 5 to 9 times higher than the nominal voltage rating.

Power arresters of the secondary type have application in communication work to protect power-operated equipment such as rectifiers, radio sets, tower warning lights, etc., against lightning and switching surges from the power lines with which they are associated. Such equipments have a relatively low insulation level and, unless suitably protected, are subject to damage caused by surges from the power line. Lines that are not well grounded are particularly troublesome in this respect.[4]

It is recommended that primary distribution lines not enter the shelter directly, that the secondary distribution transformer be shielded, that from this transformer all secondary distribution conductors be completely shielded within ferrous conduit having welded steel joints and that this conduit enter the shielded compartments or metal shelter bulkheads through welded penetrations. The shielded secondary distribution transformer referred to is one with an electrostatic shield between primary and secondary windings. All four conductors for a Wye secondary distribution should be run in the same conduit, with the neutral grounded to either the metal shelter or to the conduit where it penetrates the shelter, but should not be grounded at the other end at the exposed secondary transformer. However, the conduit should be buried and in contact with the earth. Secondary arresters are of the valve type employing a nonlinear resistance for the characteristic element.

A-4.3 Antenna Arresters

It is essential to protect communications equipment connected to exposed transmitting and receiving antennas against NEMP-induced surges. Since the problem of power-follow is not usually present on antennas, some form of spark gap is usually adequate in conjunction with a grounding system as the first-stage NEMP protection. The first stage spark gap prevents insulator damage and restores normal operation as soon as the surge threat has been reduced to a safe level. Additional stages of NEMP protection will be required to prevent transmitter or receiver burnout or breakdown. A special hybrid protector should be designed for each type of receiver-antenna input. Figure A-1 is a typical protected antenna system.

A-4.4 System Protection Versus Subsystem Protection

Individual surge protection at the point of connection of each electrical or electronic unit or subsystem to the power distribution system or signal system linkage would be both costly and unreliable, because of the difficulty of proper coordination. A much more successful approach is to provide one or more stages of surge protection at the point of entry of each power or signal conductor into the shelter facility. Properly selected surge protectors will limit voltage transients to less than twice normal peak voltage. This is adequate to protect most circuit components against failure from short duration induced transients on incoming conductors. Some additional protection will be required for unusually sensitive units, or to reduce induced or reradiated transients in particularly sensitive or critical circuits.

A-5.0 SURGE-PROTECTION DEVICES AND NETWORKS

A-5.1 Spark Gaps

A-5.1.1 General Characteristics

The most straightforward and least sophisticated circuit protector is a spark gap, which consists of several spaced electrodes surrounded by air or some other gaseous dielectric. The electrodes are tied between the lines to be protected and some grounding system. The gap protecting a line is adjusted to conduct at a voltage across its electrodes higher than the peak value (by approximately 1-1/2 times) of the line voltage. Since circuit protectors must normally be designed for each specific application, considerable background information is being provided about their characteristics. The most serious concern when using a spark gap protector is the range of voltages over which it will conduct. The sparkover voltage is dependent upon gap shape, composition, and pressure of the dielectric, and the voltage-time wave shape of the applied voltage surge (particularly the leading edge).[3,5]

If the voltage wave is rising rapidly, the sparkover voltage will be higher than for a slowly rising wave. Figure A-2 shows the effect of three different input voltage wave fronts (e_1, e_2, and e_3) along with the voltage and time at which the gap sparks over or conducts. Wave front e_1 represents a voltage that rises slowly, producing gap sparkover after a time t_1 at voltage Vs_1. A wave rising more slowly than e_1 would still cause gap sparkover at essentially the same voltage, but after a longer period of time. The more rapidly rising wave front of e_2 would cause gap sparkover at a higher voltage, Vs_2, but in a shorter time, t_2. The wave front of e_3 rises even faster, causing sparkover at Vs_3 at time t_3. The curve of Figure A-2 describes a typical relationship between sparkover voltages and the corresponding time-to-sparkover for a particular spark gap geometry. A similarly shaped response or voltage-time characteristic can be developed for any type of spark gap, and partial information of this type will be supplied by the manufacturer on commercial gas filled gap-type protectors. Although the voltage-time curve of Figure A-2 represents a typical spark gap response, the following comments point out a number of characteristics which apply to spark gaps in general:

1. For spark gaps in air, the long-time sparkover voltage (Vs_1) is not less than about 300 volts.

2. With practical gap spacings using metal electrodes and air at atmospheric pressure as the dielectric, Vs_1 is generally about 1,000 to 1,500 volts.

3. The amount by which the sparkover voltage at short times exceeds the long-time sparkover voltage (Vs_1) is called the voltage-time turn-up.

4. The greater the gap spacing, the greater the voltage-time turn-up value becomes.

5. Gaps with non-uniform fields, that is sharp-edged gaps, exhibit a higher turn-up and have a lower long-time sparkover voltage Vs_1 than do gaps with smooth contours and uniform fields.

6. Small gaps, of the type potentially suitable for protection of control and communications systems, show small turn-up values even at wave front rise times of a few tenths of a microsecond. Large gaps capable of protecting transmission lines require correspondingly longer rise times of several microseconds in order to provide similar small turn-up values.

7. Reducing the pressure of the air dielectric lowers the long-time sparkover voltage (Vs_1), but increases the turn-up proportionately. The time required for the spark to form increases as the gas pressure is decreased. Sparkover can be considered an avalanche ionization process; if the dielectric is less dense, the ionization potential to start the avalanche is lower, but more time is taken for ionization to reach a maximum.

8. By using gases such as neon as the gap dielectric the long duration sparkover voltage (Vs_1) can be made smaller than 300 volts, but the turn-up will be increased proportionately. The addition of radioactive isotopes to the discharge medium will reduce the voltage-time turn-up, stabilize the gap, and ensure a precise, repetitive response.

9. Once ionization of the dielectric media of a spark gap is fully established, the gap impedance drops to comparatively low values, the discharge conducts current, the gap maintains a practically constant low voltage across its electrodes, and the gap will not automatically deionize.

Gas-filled spark gaps have the characteristic that the sparkover voltage can be made quite low in a controlled manner. Sparkover voltages as low as 100 volts are possible on a repetitive basis. In addition, this type of gap combines very fast response (can be less than 0.1 microsecond for small gaps) with bilateral response characteristic. (Only one required to give bi-polar protection). The gas-filled spark gap is recommended primarily for signal line applications ahead of a filter or other high impedance protective device.

A-5.1.2 Spark Gap Heat Energy

The energy developed as heat in a spark gap should be minimized. This can be done in two ways:

1. Limit the fault current through the spark gap. Most of the current passed by the device comes from the power-follow rather than from the surge which made it operate. From this standpoint the greater the impedance at the power frequency between the spark gap and the power source generator the better. Optimum protection against over voltage is attained when the spark gap is placed as close as possible to the load that is to be protected.

2. Interrupt the follow current through the gap as soon as possible after sparkover. One way to interrupt the follow current is to partially enclose the spark gap in an insulating tube. The sequence of voltage waveforms occuring as a result of such a gap is illustrated in Figure A-3.

A-5.1.3 Advantages of Air Dielectric Spark Gaps

1. Simple, reliable, and inexpensive.

2. High-current handling capability.

3. Very low voltage drop during conducting state. The voltage across the arc is typically 10-20 volts.

4. Bilateral operation - same characteristics on either polarity.

5. Fast response time.

6. Relatively unaffected by radiation.

7. No auxilliary equipment, power supply or maintenance is required.

A-5.1.4 Disadvantages of Air Dielectric Spark Gaps

1. Relatively high sparkover potentials are required.

2. Inherently, simple gaps are not self-extinguishing. The arc must be extinguished externally by removing the voltage in some manner. This can be done by circuit breakers or fuses, use of nonlinear series resistors (valve arresters), or gas-blast deionizers. With proper design (for example, a design that makes use of the magnetic blow-out principle) gaps can be made self-extinguishing, but will also be considerably more costly.

3. Inexpensive spark gaps are seldom available in conveniently packaged assemblies, because they must be designed for each specific application.

4. Spark gaps in air are sensitive to variations in atmospheric conditions, and to fouling by dust or other foreign particles.

(Hermetically sealed units do not have this disadvantage).

A-5.1.5 Advantages of Gas-Filled Spark Gaps

Gas-filled spark gaps can be used as surge suppressors for particular applications. Some of their advantages can be summarized as follows:

1. Low cost.

2. Physical size is small.

3. Low sparkover voltage-typically 60-100 volts in firing times greater than 2 microseconds.

4. Can pass high currents for a short time.

5. Usually self-healing.

A-5.1.6 Disadvantages of Gas-Filled Spark Gaps

1. Poor voltage-time turn-up characteristics.

2. Will continue to conduct if the driving voltage is above 60-100 volts.

3. Possibly more sensitive to radiation than spark gaps in air at atmospheric pressure.

4. Will not absorb large amounts of energy.

A-5.2 Valve Arresters

The valve arrester, which is in common use on primary power distribution lines as a secondary arrester is a simple modification of the spark gap. In this type of arrester, a resistor is connected in series with the spark gap. The resistor may be a nonlinear element such as silicon carbide or a heavy non-inductive shunt type resistor element.

The nonlinear resistor has the characteristic current relationship $I = KV^n$, in which I and V are the current and voltage drop, respectively, and the exponent n ranges typically between 2 and 4. K is a characteristic constant of the particular resistor material.

This relationship predicts that a high voltage surge will, in effect, reduce the resistance and allow heavy current to flow to ground through an arrester when the surge initiates the power arc. Some manufacturers claim that a properly designed non-inductive linear resistor is a more stable and reliable quenching element and use this in their lightning arresters. The sequence of voltage waveforms associated with a valve arrester is depicted in Figure A-4.

The voltage rating of a standard arrester is the maximum rms voltage-to-ground at which it will interrupt follow current, and not the sparkover potential. The "impulse sparkover potential" rating of an arrester is based upon a nominal 1-1/2 x 40 microsecond test wave (1-1/2 microsecond to crest and 40 microseconds wide at half amplitude) and may be 5 to 9 times higher than the nominal voltage rating.[4]

A-5.2.1 Advantages of Valve Arresters

1. Self-extinguishing.

2. Available off-the-shelf under standard ASA classification as "secondary type arrester".

A-5.2.2 Disadvantages of Valve Arresters

1. Relatively expensive.

2. Greater physical size as compared to regular gaps.

3. Voltage across its terminals always higher than a gap alone.

A-5.3 Semiconductors as Clamp (or Crowbar) Devices[5]

Clamp, or crowbar devices include the group of semiconductors, such as zener diodes and silicon-controlled rectifiers (SCR's) which conduct abruptly upon avalanche breakdown or upon triggering. Since the impedance of these devices collapses to a very low value when they conduct, it will often be necessary to add a series impedance to dissipate the surge energy and limit the magnitude of the power-follow current through the deivce. A nonlinear resistor (varistor) such as silicon-carbide is very effective for this purpose. An SCR crowbar protector is shown in Figure A-5.[6]

A-5.3.1 Advantages of Semiconductor Devices

1. Good surge current ratings, although not as good as spark gaps.

2. Low-voltage drop when conducting.

3. Excellent repeatability and reliability as long as ratings are not exceeded.

4. Avalanche diodes will begin conduction at a predictable low voltage. Avalanche voltage ranges are available from 3 to over 100 volts in this type of device.

5. Suitable for use on low-voltage DC circuits.

6. If properly applied to AC circuits, will interrupt follow current at first power current zero following the initiation of conduction.

A-5.3.2 Disadvantages of Semiconductor Devices

1. Low thermal capacity to dissipate surge energy.

2. Must be triggered by auxiliary circuit.

3. Will not interrupt follow current on DC circuits.

4. Limited in rate of build-up of current or rate of build-up of voltage which can be tolerated.

5. Costly-A 100 ampere epitaxial SCR typically costs $50 to $100 depending on its voltage rating.

6. Not bilateral. For protection on both polarities, two rectifiers and additional circuitry must be used. Bilateral devices are available. These are two SCR's back to back, called Triacs.

A-5.3.3 Thyrite and Thyrectors

Thyrite is a silicon carbide material. Thyrectors are selenium rectifier devices. When Thyrite or Thyrectors are used on an AC power system, they are not able to limit surge overvoltages to values as low as or less than the peak value of the steady-state voltage.

If a surge spike equal to twice the peak value of the steady-state operating voltage occurs on an AC power system and this spike occurs at the instant that the steady-state voltage is at a positive peak, the protective device will attempt to limit the voltage. If, however, the surge (positive going) spike occurs at the instant the steady-state voltage is at a peak negative value, the protective device will have no effect. This is because the absolute value of the sum of the steady-state voltage and the surge spike voltage is equal to the peak value of the steady-state voltage.

The energy dissipation capability of the Thyrite or Thyrectors is determined by their ability to dissipate the heat generated by the current flowing through them. In Thyrite this dissipation is determined by the total volume of Thyrite material. A typical Thyrite element for use on 120 volt AC systems would be a disk of dimensions, 6 inches in diameter and .375 inch in thickness. The maximum allowable steady-state current through the disk is determined by the surface area of the disk which is exposed to the air. For Thyrectors the energy dissipation depends on the duration of the pulse which is forcing current through the Thyrector. For a very short pulse, the energy would have to be dissipated in the form of heat in the selenium material itself.

However, for longer duration pulses, there would be sufficient time for the heat buildup to diffuse out onto the cooling plates of the unit and this means, that for longer duration pulses, the energy dissipation capability of the Thyrector is increased over that for short duration pulses.

A-5.4 Carbon Block Type Protectors

The term "protector" as commonly used in communication applications denotes a two terminal device providing means of circuit connection and mounting two closely spaced electrodes. One example of this is the ordinary fuse block which mounts a line fuse. Another is the carbon block protector, one type of which is shown in Figure A-6.

Carbon has proven to be the most satisfactory electrode material for general use. Electrodes are presently composed of finely divided carbon held together by a binder with an arcing surface melting temperature of 3500°C and having the ability to sublime at high arcing temperatures. The carbon electrodes form a low voltage, high current arc upon breakdown and allow thousands of amperes of current to be shunted to ground; upon extinguishing of the arc, the carbon gap usually remains open without bridging from residue.[4] With numerous repeated operations, the carbon gap will usually bridge and form a short and must be replaced. However, this feature gives the carbon gap device a "fail safe" characteristic.

Existing transient overvoltage protection for telephone signal and communications wires usually utilizes some embodiment of carbon electrodes with or without fuse elements. In-service experience with carbon block arresters in telephone lines has indicated that pitting and build-up on the electrodes occur due to the discharge of accumulated static charges on long lines over a period of time. In most cases individual line arresters which are faulty will introduce noise on the line and, as a result, can be readily identified. The design of these arresters is such that they can be quickly replaced when it is found to be necessary.

The limiting voltage obtained across a protector's terminals will depend on the volume resistance of the electrodes, the magnitude of the discharge current, the impedance of the mounting and grounding circuit and the voltage drop across the carbon arc (about 25 volts). For a typical NEMP pulse induced in the protected circuit, the resultant voltage wave form will probably be a sharp spike of over 1,000 volts peak decreasing exponentially in a few microseconds to about 50 volts. For such a threat, a telephone circuit would probably survive repeatedly without damage but more sensitive communications and control circuits will require additional backup protection.

It will usually be necessary to replace existing grounding circuits for these carbon block protectors, with better designed impulse grounding grids.

A-5.4.1 Advantages of Carbon Block Protectors

1. Presently provided for most telephone, control, and signal wires.

2. "Fail Safe" operation.

3. Inexpensive.

4. Reliable with low maintenance requirements.

5. High current handling capabilities.

A-5.4.2 Disadvantages of Carbon Block Protectors

1. High sparkover voltage requirements, with voltage turn-up effects with fast rise-time pulses.

2. Not usually designed for shielded circuit applications as will normally be required for NEMP protection.

3. Application limited to low voltage, low current circuits not requiring power follow interruption.

A-5.5 Filters

Filter or isolator elements will normally be required on low-current and low voltage conductors which penetrate outer enclosure shielding in order to provide NEMP protection for those communication and electronic equipments with narrowband susceptibility characterisitcs and those which are unusually sensitive to very low energy pulses (computers, radio receivers, solid state instrumentation, etc.). The filters should have one or more preceding stages of voltage limiting protection, depending on the shielding and exposure of the conductors prior to entry in the shelter. The purpose of the additional stages preceding the filter is to protect the filter elements from damage. A series inductor preceded by an arrester-type protector is typical of protection to be used. If the filter has an inductive input, the extra series inductor will probably not be necessary.

The design of these filters must necessarily be compatible with the band spectrum requirements of the connected equipment. It is desirable to suppress all frequencies outside of the required band spectrum.

A-5.5.1 AC Power Filters[6]

AC Power Filters when required for protection of equipment connected to 60 Hz, 115 VAC power should be located on interior shielded enclosure bulkheads at points of conductor penetration. They may not be required

on very insensitive electrical equipments whose power conductors are shielded in ferrous conduit all the way from the generator to the equipment. If protection against NEMP is the only reason for needing a filter, the AC power filter would probably not be chosen since it gives very little isolation to low frequency transient pulses.

AC power filter response curves measured as described in MIL-STD-220A should have a rising slope to greater than + 3 db at 1 KHz and with no negative values. This will help prevent resulting insertion gain when the filter is installed in an impedance mismatch system. AC power filters normally are expected to exceed 100 db attenuation from 14 KHz to 1 GHz. The following are some desirable characteristics of AC power filters to be used where large transient voltage pulses are anticipated:

1. Filters should employ inductive inputs and capacitive outputs. The inductor assures firing potential for the preceding arrester and limits the current through the filter capacitor. The input inductor in these filters should be single-sweep wound and employ adequate spacing between start and finish leads to withstand a 5,000-volt transient breakdown test. It should have its core taped with suitable insulating material (preferably Teflon tape) to withstand 5,000 volts from the winding to the core. Cores should be of powered iron or molybdenum permalloy material. The inductor windings should employ heavy Formvar or heavy Soldereze wire only.

2. The capacitors in these filters should be of the self-healing Mylar or metalized Mylar construction and should have a breakdown voltage of not less than 600 VDC.

3. Potting material should be high-temperature (125°C) wax or heat-conductive epoxy. Oil (except for flame-retardant silicon oils) or foam material should not be used.

The theoretically derived insertion loss curve for an inductive input AC power filter which has been specifically designed by its manufacturer to give 100 db insertion loss 14 KHz to 10 GHz when placed in a power circuit with 0.5 ohm or less power source impedance, and with rated load drawing 25 amperes resistive, is given in Figure A-7a and designated as unmodified. Parallel damping to reduce ringing caused by voltage pulse type signals has been added by the author to this filter in the form of 10 ohm and 211 μh resistive and inductive components placed in parallel with the three normal filter inductors.

The circuit diagram for this modified filter is also shown in Figure A-7a along with calculated and measured insertion loss curves for the modified filter. The voltage-time response of this same damped filter installed in a typical shielded enclosure installation to a large voltage spike is shown in Figure A-7b for a lightly loaded and fully loaded filter. Similarly the insertion loss curves and voltage-time

response of another AC power filter, undamped and of poorer design, is shown in Figures A-8a and A-8b. The latter response is typical of operational installations of AC power filters designed to give maximum performance into 50 ohm source and load impedances and with inductors that badly saturate at full rated load. Results of studies show that many commercially available AC power filters ring at those frequencies where the insertion loss curves show resonant peaks of gain in the pass band, or lower frequency below cut-off portion of the insertion loss curves.

It would be beneficial for AC power filters used in EMP hardened facilities to have some added means for internal damping such as that shown in Figure A-7a. Also the impedance of the power source and load between which the filter is to be installed should be considered as part of the design criteria for the filter in order to result in the desired filter response characteristics.

A-5.5.2 DC Filter Protection

DC filters should have the same characteristics stated in section 5.5.1 except that capacitors need only be rated at 200 VDC. DC filters should be preceded by spark or gas-discharge arresters.

DC lines may also be protected by transient bucking transformers, connected as shown in Figure A-9. This scheme is especially effective in the protection of DC-to-DC converters from burnout due to collector-emitter overvoltage (V_{ce}) resulting from line transients. Adequate line-to-ground protection should be provided ahead of the transient bucking transformer.

A-5.6 Relays and Circuit Breakers

Electromechanical devices should never be relied upon for NEMP protection. Because of the mass of moving parts, response is far too slow for NEMP transients. Circuit breakers are not suitable because there is not enough assurance that the series gap will not arc and reclose the circuit on the transient; also, service is interrupted unnecessarily, and the breaker will not respond fast enough if it is electromechanical.

A-5.7 Special Problems of DC Protection

DC circuits are very likely to employ semiconductor regulators or other protective circuits which are very susceptible to line transients. The presence of polarized capacitors such as those made from tantalum invites disaster if any significant reverse transients occur. This type of susceptibility suggests the use of hybrid circuits. Special power interrupting or quenching circuits will be necessary to release SCR's from power-follow currents.

A-5.8 Pulse Stretching - Low-Pass Filters-Lossy Lines

The effect of voltage wave form rise-time on the breakdown voltage of gaseous-type protection devices was treated earlier. From this treatment we can see that the most ideal operation of these protectors occurs when the rise time of the impinging voltage pulse is long. When this occurs the protector limits the overvoltage to its lowest possible value. It will be very desirable if means can be used to assure that any voltage pulses induced on incoming conductors which need protective devices are pulses with long rise time (for example, much greater than 1 microsecond).

Pulse rise-time lengthening is usually accomplished by low-pass filters or by other devices which have the characteristics of low-pass filters, since the fast rise-time portion of the wave form contains higher frequencies than a slower rise-time wave front. The normal conductor is a low-pass filter because of the so-called "skin effect", or AC resistance, which increases with frequency. Also, the smaller the conductor radius the greater the AC resistance. For a transmission line above ground and the line-to-ground mode of propagation, the ground losses add significantly to the conductor losses so that most transients which travel long distances on conductors lose the higher frequency components and have longer rise times.

The "lossy line" was developed and patented by NCEL[8] to greatly accentuate skin effect in conductors. Figure A-10 shows the change in rise time for a simulated lightning surge transient on a 1/2 mile lossy line at the beginning, middle, and end of the line. This type of power conductor would be excellent for pulse stretching ahead of NEMP arresters and protectors. The most recent development of this line, which has a spiral threaded copper tape wrapping plus the SiFe tape is shown in Figure A-11a. The conductor in Figure A-11a is AWG 3/0 equivalent, and was installed in a 13 KV overhead line. The shielded cable in Figure A-11b is AWG 1 equivalent and was installed in a 13 KV buried feeder. The measured attenuation as installed is shown in Figures A-12a and A-12b as a function of frequency and units of length (per mile). This development is described in detail in NCEL report R-444.[8]

The use of this shielded conductor (Figure A-11b) is recommended for underground secondary distribution in the approach to typical hardened communication centers at approximately 13 KV to provide pulse stretching and suppression prior to arresters or protector devices. This lossy cable can be obtained for less than twice the price per unit length of similar but untreated cables.

A-6.0 APPLICATION OF SURGE PROTECTION

A-6.1 Classification of Circuit Protection Limits

Before any plan of protection can be instigated, it is necessary to ascertain the characteristics of the most susceptible piece of equipment

in a given area. It is assumed that the areas to be protected consist of metal shielded compartments within the main enclosures, each compartment containing some type of electronic equipment. The most sensitive piece of equipment in a compartment will determine the class of protection required for the entire shielded compartment. Each compartment will thus have a level or class of protection designed for its own particular requirements. For example, if a single room contains a motor generator set, a calrod heating system, and an electronic computer, the protection scheme will obviously be designed to accommodate the computer. For this reason, it is imperative to group equipment with similar protection requirements in the same enclosure to reduce the number of advanced protection systems required.[6]

The leads penetrating a given compartment will be divided into three groups: AC power, DC power, and signal lines. Figure A-13, Figure A-14, and Figure A-9 illustrate typical examples of protection for these three groups.

Table A-II shows the classification of various types of equipment and the general class of protection required for each type of equipment under an "extreme threat" environment. The information presented here is of a general nature and, therefore, all available susceptibility information should be obtained for a specific piece of equipment before the general class of protection to be used is finally determined.

A-6.2 Special Equipment Protection Requirements

One of the most important considerations for protection of a given piece of equipment attached to the power line is the characteristics of its power supply. With regard to NEMP transient susceptibility, a few observations concerning power supplies may be made.

Power supplies which are designed to operate from a broad frequency range (50 to 1,000 Hz) should be avoided. These wide-range power supplies contain transformers with much lower leakage inductance than those that operate only from 50 to 60 Hz power sources. The leakage inductance in the power transformer will contribute to the suppression of conducted transients on the power line because this leakage inductance is reflected in series with the primary winding.[6]

Power supply susceptibility may be reduced by adding approximately 1 microfarad of capacitance (non-polarized) across each of the secondary windings of the power transformer. This capacitance forms an "L" type low-pass filter with the leakage inductance.[6]

Power supplies employing bridge or full-wave rectifier assemblies should preferably use controlled avalanche-type diodes or vacuum tube diodes. This type of rectification system is much less likely to suffer damage as a result of an overvoltage condition than is a conventional semi-conductor diode assembly.

The term solid state (when applied to a power supply) usually means that an electronic regulation scheme is employed that used transistors or integrated circuits or both. Because of the inherent sensitivity of

TABLE A-II

Equipment Protection Requirements (Extreme Threat Level)

CLASS 2 Protection (Insensitive)
Motors - AC Induction Lamps - filament and fluorescent Heaters, coffee pots, air conditioning equipment Motors - series and shunt-wound Meters, line voltage, line frequency Isolating motor generator sets 60-400 Hz converters
CLASS 3 Protection (Moderately Sensitive)
Vacuum tube AC power supplies in general Teletype equipment power supplies Transmitter-high-power RF (over 50 watts) power supplies Vacuum tube receivers-all types (power input) Vacuum tube differential input circuits (signal) Solid-state receivers with isolation provided Alarm system power Intercom power-vacuum tube Telephone signal lines
CLASS 4 Protection (Sensitive)
Computer power - all types Solid-state power supplies in general Single-ended or unbalanced coaxial system inputs Computer-line inputs - all types Alarm system control leads Intersite intercom signal leads Antenna tracking system power Antenna tracking control leads Radar system power (and control if applicable) Intercom power - solid state

NOTE: Class 1 will refer to normal lightning protection, as applied to existing installations such as power transmission lines.

solid-state devices to overvoltage damage, it is imperative for protection from NEMP transients that the aforementioned measures be employed whenever solid-state regulation is involved. Investigation of the type of protection employed by manufacturers of solid-state equipment will reveal some very adequate systems. For example, Fairchild-Electro-Metrics Division powers their electromagnetic interference (EMI) receivers on batteries continuously, and the AC power supply serves only to charge the batteries when power is available. Such a scheme affords excellent NEMP protection, since the AC power supply components could be damaged by a transient and the equipment would continue to operate on battery power.[6]

DC-to-DC converters are susceptible to damage of the "off" state transistor resulting from incoming line transients. Such transients appear in addition to the "off" state collector-emitter voltage V_{ce}, which is nominally twice the power supply line voltage (see Figure A-15).

The transient bucking transformer shown in Figure A-9, in combination with a capacitor across the input leads of the converter, should be a very effective transient-suppression scheme. It is important, however, that the low voltage side of the inverter input not be grounded to the shield or protector ground, or the bucking winding of the transformer will be shorted.[6]

A-7.0 RECOMMENDED PRACTICES FOR INSTALLATION OF SURGE ARRESTERS

A-7.1 Optimum Placement of Surge Arresters

Surge arresters should be installed on the high-voltage or primary side of the power distribution transformer whenever possible. When this is done the voltage amplitude of the surge arrester output will be reduced by the turns ratio of the transformer. A general output of the power distribution protection for a typical installation is shown in Figure A-16.

A-7.2 Grounding of Surge Arresters and Protectors

Since most induced surges occur from line to ground rather than phase to phase, arresters are designed for line-to-ground installation. For this reason, it is essential to provide an adequate low RF impedance grounding system for the arrester. If the power distribution system is properly designed, all conductors will be contained within ferrous conduit which terminates in welded bulkhead penetrations of metal compartments which are themselves adequate grounding systems for the arrester or protector. Within a shielded protective shelter, surge protector grounding should be the metal shield of the same small shielded compartment containing the protector. This small compartment should be bulkhead mounted on the interior of the shielded enclosure at the point of penetration of conduit and conductors. A bolted access panel with an

RF gasket should be provided for access to the protectors (one for each phase). If the neutral is also contained within the conduit, it should be grounded to the metal bulkhead or shield near the point of penetration and still within the inner conduit wall, junction box, or surge protector shield. Power conductors leaving the surge protector shield should, if possible, do so within ferrous conduit run adjacent to metal floor, walls, or ceiling, with numerous grounding ties to the shield. Neutrals or ground returns are normally not adequate for grounding of arresters and protectors.

A-7.3 Protection of Neutrals and Ground Returns

Low-voltage protectors on the secondary side of power distribution transformers should be located as close to the penetration of the leads through the shield or metal bulkhead as possible.

Low-voltage protectors should be located on the inside wall of the shielded enclosure for access when replacement is necessary. A convenient location for the protector would be in the AC power filter can input chamber, which is mounted on the inside bulkhead of the shielded room at the point of conductor entry. The protector must be totally shielded.

A-8.0 PERSONNEL SAFETY

A-8.1 Electric Shock

Electric current passing through the body rather than the magnitude of the voltage contacted determine the intensity of the electric shock. Voltage is significant only in so far as it is one of the factors determining the magnitude of current established in the body of a person contacting an energized circuit. In addition to voltage, shock current is a function of the impedance of the circuit contacted plus the body impedance of the victim.

Investigations of shock intensity from transient potentials indicate that the heart is not damaged unless the transient energy exceeds about 50 watt seconds.[4]

A-8.2 Protection of Personnel

The potential danger to operating personnel from transient shocks during illumination of the area by the NEMP field can be reduced by utilizing the following design features:

1. Electrical insulation layer, such as neoprene sheet, on floor;

2. Non-metal chairs, cots, desks, and tables;

3. Flush-mounted equipment racks, cable trays, metal piping, and large metal objects against metal bulkheads;

4. Layout of equipment racks and large metal objects so that operators do not stand or reach between them;

5. Use of individual power filters for apparatus or equipment if required with inductive input rather than capacitive.

A-9.0 METALLIC OBJECTS

All sizeable metallic objects, such as water pipes, conduit, shielded cables, metal stacks, tanks, motors, pumps, and metal doors, should be bonded to the shield with a minimum length of flexible copper braid or other flexible metal conductor compatible with the shock mounting. Banks of interconnected metallic objects, such as continuous racks of equipment having good electrical continuity, may be bonded to the room shield at each end of the bank. Structural members of antennas and metal waveguides installed inside the building should be bonded to the internal metal shield. Multiple grounding is preferred to single-point grounding. Grounding conductors should be as short as possible, flexible to the extent required, and connected at the nearest possible location to the shielded enclosure skin. Ground connections should be welded or brazed.

Proper design for NEMP protection will require runs of metal piping, cables, metal ducts, conduit, and wiring flush along metal walls, ceilings, or floors, with numerous ground ties to the metal shield distributed along their length.

A-10.0 PROTECTION OF SHELTER FROM NEMP

A-10.1 Attenuation of the NEMP Wave

Induced or radiated fields generated by a nuclear explosion can cause damaging effects to electronic and electrical components or systems. The required protection of sensitive electronic equipment from fields of the magnitude anticipated can only be realized by the extensive use of shielding.

Two types of NEMP wave fields may require significant attenuation before reaching critical electronic equipment. The first occurs at close-in ranges where the magnetic field predominates, giving rise to a low impedance field. In this type of field, very little of the wave energy encountered is actually radiated, but strong induced currents can be coupled or induced into various parts of the structure. The second is the radiated field, which emanates from a distant surface burst or a high altitude burst. The impedance of this wave is identical to that of

free space (when beyond the ionized region) and is generally observed at ranges greater than those where the induced field predominates. For a continuous-wave transmitter and suitable antennas, these two regions would be known as the near and far fields, respectively. In the pulsed electromagnetic field, the induced and radiated fields will actually provide considerable energy at many discrete frequencies, depending primarily on the shape of the pulse, as well as a broad spectrum of energy which covers the frequency range from low to very high frequencies to protect against the many possible pulse components.

Shielding against a pulsed magnetic field is essentially the same as shielding against any magnetic field. The basic principle involves both scattering of the magnetic flux away from areas to be protected and dissipation of the magnetic field energy. Maximum protection from low-impedance high-intensity magnetic fields of low frequency is obtained through absorption of the wave energy in passing through the shield material.

Protection against the high-intensity electric fields is obtained primarily by reflection from the shielding surface. Generally, for optimum electric-field reflection, a highly conductive surface such as copper gives the best results.

The reduction or attenuation of either the electric or magnetic field strength due to the presence of a shielded enclosure is termed the shielding effectiveness of the enclosure. Shielding effectiveness is defined as 20 times the logarithm of the ratio of the voltage induced in a conduction loop or circuit without the shielding to that in a loop or circuit with the shielding. Shielding effectiveness (SE) is measured in decibels (dB) and is determined from the following equation.[9]

$$SE(dB) = 20 \log \frac{E_1}{E_2}$$

where E_1 is the induced voltage without shielding and E_2 is the induced voltage with shielding.

A-10.1.1 Reflection

A portion of the wave incident on an electromagnetically shielded shelter will be reflected. The amount of the wave reflected will depend on:

1. The impedance of the incident wave

2. The frequency of the incident wave

3. The electrical properties (surface impedance) of the reflecting surface

4. The distance between the source and the shielding surface

5. The electrical properties and impedance of the earth

Later additions to this report will treat ground reflection losses.

A-10.1.2 Absorption

A portion of the electromagnetic pulse energy will be attenuated in passing through the shelter wall. The amount absorbed will depend on:

1. The frequency of the wave

2. The electrical properties of the barrier

3. The thickness of the barrier

A-10.2 Shielding Effectiveness for Structures Using Steel Reinforced Concrete

Maximum shielding from an NEMP wave is attained by use of solid metal as the shielding material; however, limited shielding can be obtained from reinforcing steel and wire mesh used as construction materials. This is particularly true if the rebars are welded at joints and intersections to form many continuous conducting loops or paths around the surface of the volume to be shielded. The shielding effectiveness provided by this type shielding is proportional to the magnitude of circulating currents induced by the impinging electromagnetic field in and about the four walls, floor and ceiling of the structure.[3] The degree of shielding will depend on the following parameters:

1. The size and shape of the volume to be shielded

2. The diameter of the rebars and spacing (the distance between rod centers)

3. The electrical and magnetic characteristics of the rebar materials (conductivity and relative permeability)

4. The frequency of the incident wave

Calculations describing the shielding obtainable by use of the rebars are considerably simplified if their electrical conductivity, permeability, diameter and spacings are assumed to be within a practical range associated with reinforcing steel used for normal construction. In the following, a conductivity $\sigma = 6.5 \times 10^6$ mho/meter and a permeability of $\mu_r = 50$ have been assumed. The calculations of shielding

effectiveness are a good approximation for conductivities ranging from $4x10^6$ to $8x10^6$ mho/meter and for relative permeabilities ranging from 10 to 100. The frequency used in these calculations is approximately 10 KHz and is near the lower end of the range of frequencies anticipated.

The diameter of the rebars and center-to-center spacings will depend on structural considerations of the building design. Typical diameters have been chosen as the basis of the following calculations; ranges of diameters run from #6(0.75 inch) to #18s(2.257 inch). Spacings have been varied from 7 inches to over 22 inches. The attenuation values are valid and conservative for rebar spacings within two inches of the design spacings exceeding 14 inches. Bar diameter may vary 10% from the nominal values without serious effect on the accuracy of the shielding data calculations.

The family of curves shown in Figure A-17 describes the attenuation for an enclosure whose height is 15 feet, and its other dimensions vary over a 5 to 1 range. Figure A-18 shows the same information, except that the height of rebar with diameters of 1.692 inches and a spacing of 14 inches on center. Provisions for determining dB correction factors to Figures A-17 and A-18 for other rebar diameters and spacings are as follows, based on room proportions:

1. Height 30 feet or greater - use curves for 30 feet.

2. Height between 15 and 30 feet - use curves for 15 feet

3. For variations in width (J) dimensions - use curve equal to or just less than the required value

The room dimensions, rebar spacing, and diameters, are typical and cover most situations encountered in practice, however, the shielding effectiveness may (for a particular size enclosure) be calculated using the information in reference 3. The curves of Figure A-18 can also be applied to double-course rebar construction, if the single-course spacings are halved when determining attenuation corrections for double-course rebar construction. Some examples of corrections to be applied in various cases is shown in Table A-III.

The values of attenuation obtained from Figures A-17 and A-18, (with corrections as necessary according to Figure A-19) are those obtainable at the center of the room volume specified. There will be less shielding near the edges of the room; Figure A-20 shows the degradation which occurs as the proximity of the rebars is approached. The degradation curve is valid for room heights between 15 and 45 feet and lengths ranging from 45 to 300 feet; it is also suitable for use with solid steel plate and wire mesh constructions.

A sample calculation will point out the use of the various curves of this section. To determine the center area attenuation and the attenuation near a wall for a single-course and double-course reinforcement bar type construction, assume the following:

TABLE A-III

Applicable Attenuation Factors for Rebar Constructions[3]

(as obtained from Figures 17 and 18)

REBAR DIAMETER INCHES	REBAR SPACING INCHES	TYPE OF CONSTRUCTION	ATTENUATION DECREMENT FROM FIG 19 ΔdB
2.257	12	SINGLE-COURSE	+5
1.692	14	SINGLE-COURSE	0
1.000	18	SINGLE-COURSE	-6
2.257	20	DOUBLE-COURSE	+8.5
1.692	14	DOUBLE-COURSE	+13
1.000	16	DOUBLE-COURSE	+5

1. H = 18 feet

2. J = 32 feet

3. L = 145 feet

4. σ and μ_r are within the values specified, i.e.,
   $\sigma = 6.5 \times 10^6$ mho/meter, $\mu_r = 50$

5. Rebar diameter = 1.41 inches ± 10%, Rebar spacing = 15 inches, center to center

A-10.2.1 Single-Course Rebar Construction

Since H = 18 feet, use curve for H = 15 feet, Figure A-17. J = 30 feet, and L = 145 feet, read attenuation of 24.5 dB. For 1.41 inch diameter rebar on 15 inch centers, apply correction factor of minus 2dB (from Figure A-19). Thus, the center area attenuation is 24.5-2 = 22.5dB This will be the attenuation in the room beyond six feet of the shielding rebars.

Assume that the rebars used are near the outside of the wall so that there is a wall thickness of 18 inches (=1.5 feet) between the rebar and an equipment cabinet. The attenuation at this point (from Figure A-20) would be 22.5 - 3.5 = 19 dB.

A-10.2.2 Double-Course Rebar Construction

1. Center area attenuation = 24.5 dB (from Figure A-17)

2. 15 inch spacing, 1.41 inch diameter; read from Curve F Figure A-19, 7.5 inch spacing
   (For double rebar) = 9.2 dB

3. Total attenuation = $\overline{\text{33.7 dB}}$ for double rebars

For equipment against the wall, assume the inner rebars are 3 inches = 0.25 feet from an inside wall of the room. Figure A-20 gives -10 dB for this distance. The net shielding at this point is 33.7 dB-10 dB = 23.7 dB.

A-10.2.3 Use of Welded Wire Fabric for NEMP Shielding

Welded wire fabric imbedded in the walls of a room or building can provide attenuation if the individual wires of the fabric are joined to form a continuous electrical loop around the perimeter of the area to be shielded. At each seam where the mesh meets, each wire must be welded or brazed to the corresponding wire, or the meshes may be connected by a continuous strip. Openings will require the same type of consideration

as discussed in section A-12. Additional attenuation of the undesired electromagnetic pulses may be obtained by use of a double layer of welded wire fabric separated by the thickness of a regular wall.

A-10.2.4 Attenuation Calculations for Welded Wire Fabric

The attenuation at the center of the enclosed room for welded wire fabric can be obtained from the same set of curves used to determine values for reinforcing steel bars (Figures A-17 and A-18). An attenuation increment will be necessary, as indicated by Table A-IV.

TABLE A-IV Application Factors for Welded Wire Fabric

Wire Diameter	Spacing	# of Courses	Attenuation Increment
0.135 inches	6 inches	1	-3 dB
0.135 inches	6 inches	2	+4 dB

See reference 3 for calculation of other wire diameters and spacings.

A-10.3 Commercial Shielded Enclosures

Several firms produce shielded rooms which will give some protection from the direct NEMP fields. These rooms are generally custom made to fit into a particular space and generally form a shielded room inside a larger building, since most of them are designed for indoor use only.

The most satisfactory construction type available is welded construction using 1/10" sheet steel (or heavier) with over lapping seams.

Figure A-21 shows typical in-place construction section and details of a welded liner in reinforced concrete construction.[19] Low temperature metal inert gas welding is preferred. Also available are portable demountable shielded rooms with armored plywood panels and with special bolted seams which secure successive panels both electrically and mechanically.

From a shielding standpoint, doorways, piping penetrations, conduits, air conditioning ducts, wave guides, etc. will adversely affect these enclosures. For this reason, the manufacturer will generally require working drawings showing the configuration of the shielded volume as well as the sizes, kinds and placement of openings and penetrations before engineering the shielding at some specified level.

Commercial NEMP shielding should be evaluated by measurement of its ability to attenuate low impedance magnetic fields over a typical frequency range 10 KHz to 10 MHz in accordance with the procedures stated in the latest revision or superseding document(s) of MIL-STD-285.

The shielding effectiveness obtainable from commercially available custom-designed rooms will vary, depending on the type of construction,

the size of the room, the quality of the doorways, the number and type of penetrations, etc. A number of representative enclosures have been measured for performance in the frequency region considered critical for NEMP work. Table A-V shows the results of magnetic field shielding effectiveness tests of some typical in-service shielded enclosures, along with a brief description of the room tested.

A-11.0 METHODS FOR GROUNDING THE SHELTER

Grounding for purposes of protection against NEMP must necessarily take on the aspects of impulse grounding. As such, the impulse or transient characteristics of an established grounding system or grounding counterpoise should be considered and not the leakage, or low-frequency, resistance. Available information on the impulse characteristics of grounding systems has been considered originally from the standpoint of lightning protection.[10]

If the voltage gradient produced by the current pulse into the ground through the grounding system is about 350 kV/ft or greater, soil ionization may take place, and the effective size of the grounding system may increase temporarily, with a resultant slight decrease in impulse resistance. It is not anticipated that soil ionization will play a significant role in grounding systems for NEMP.

A low-impulse impedance grounding system or counterpoise will be needed at each location where an arrester or protector is used to limit overvoltage on an external line or conductor. One such location is the point where commercial power lines enter the first shielded step-down transformer.

A low-impulse impedance ground will be needed for the shelter itself, generally at a point where external conductors enter and protectors or arresters are located. Suitable shielded room grounds may be obtained by reference to Figure A-22 where a typical grounding method is depicted.

A-11.1 Transient Response of Grounding Systems

The transient response (surge impedance) of a grounding network decreases exponentially with respect to time when the network is conducting a typical transient current impulse. Initially, the effective resistance is relatively high. This is defined as the "initial surge impedance". As the pulse propagates along the conductors of the counterpoise from the point of initiation and enters the earth, the surge impedance at the input point of the counterpoise decreases progressively, eventually reaching the steady-state condition at the leakage, or low-frequency resistance.

Ground rods have the advantages of immediate and intimate contact with the earth, but the disadvantage of having to be driven at each and every point an earth ground is required, which introduces problems of placement in rocky soil or rock strata. The counterpoise has the advan-

TABLE A-V

Typical Shielding Values for Commercially Available Shielded Enclosures.

RANGE OF SHIELDING EFFECTIVENESS MEASURED (dB) (MAGNETIC FIELD DATA)				GENERAL DESCRIPTION OF ROOM TYPE IDENTIFIABLE CHARACTERISTICS
ITEM	MAX	MIN	FREQ KHz	
1.	61. 97.	56. 95.	15. 200.	Copper screen cell type (now obsolete)
2.	90. 87.	54. 63.	15. 150.	Styrafoam core sheet metal skin Braided gasket material for door bonding.
3.	100. 118.	81. 108.	15. 200.	Hollow core construction. Piano hinge on door with finger stock.
4.	100.	80.	1000.	29 Mil sheetmetal bonded to 3/4" plywood Base Panel (2 sides) with bolted seam clamps. Three point suspension on personnel door. 20x50 foot overhead door with double row finger stock.
5.	93. 120.	64. 95.	18. 150.	Construction similar to item #4 above, except no overhead door.
6.	58. 75.	34. 58.	14. 280.	26 Gauge steel w/folded and soldered seams between panels. Commercially available door with double row of beryllium copper fingerstock. All power lines provided with filters.
7.	70. -	65. 90.	14. 100.	Continuously soldered 20 gauge sheet metal with 1.25 oz/ft^2 zinc electroplate. Two commercial doors with fingerstock (2 rows). Power line filtering installed. Room size = 20x20x8 feet.[11]

TABLE A-V CONTINUED

RANGE OF SHIELDING EFFECTIVENESS MEASURED (dB) (MAGNETIC FIELD DATA)				GENERAL DESCRIPTION OF ROOM TYPE IDENTIFIABLE CHARACTERISTICS
ITEM	MAX	MIN	FREQ-KHz	
8.	90. 130.	74. 106.	14. 200.	Continuously welded (MIG) sheet steel, #12 gage with overlapping seams. Standard commercial shielded room door with double row fingerstock.[16]
9.	111. 99.	50. 81.	15. 100.	Similar to #8 in construction features.[15]
10.	 62. 108. 120.	25. 52. 92. 107.	0.1 1.0 15. 100.	Double shielding of #10 gage continuously welded (MIG) low carbon sheet steel, 2" spacing between shields, pneumatic bladder, expanding panel sliding doors. (No Gasket).
11.	104. 122. 80. 39. 20.	73. -- -- -- --	15.0 10.0 5.0 1.0 0.50	Room partitioned into three separate rooms; two are 12'x12'x10' and the third is 12'x12'x14'. All seams continuously welded (MIG)#16 gage sheet steel. Doors have pneumatic bladder with triple row of finger stock.
12.	>115. >114. >140. 119.	-- 104. 114. 61.	10,000. 100. 15. 1.0	Room divided into three cells. Single shielding, sheet steel continuously welded (MIG), with pneumatic bladder, and expanding panel sliding doors (RFI gasket for contact surface). Total room size 30x70x12 feet.

tages of being easy to connect and install. The main disadvantage of a counterpoise is the elapsed time required for intimate earth contact to be established. By properly combining ground rods and counterpoise, the advantages of both can be obtained and the disadvantages can be largely eliminated.[17]

The surge impedance for a buried conductor with a step current input is shown in Figure A-23. The second and third peaks in the impedance amplitude curves represent reflections from the end of the conductor[10].

A typical counterpoise ground for NEMP could use an 8-point star configuration. To determine the effect of the number of legs, we consider first the leakage resistance of an 8-point star, which is given by the expression[14]

$$R = \frac{\rho}{16\pi L}\left(\ln\frac{2L}{a} + \ln\frac{2L}{S} + 10.98 - .551\frac{S}{L} + \frac{3.26S^2}{L^2} - 1.17\frac{S^4}{L^4} + ..\right)$$

where L = length of each leg, ρ = resistivity, a = conductor radius, and S/2 = depth of burial.

If L = 100 feet, S/2 = 10 feet, ρ = 1,000 meter-ohms, and if 4/0 wire is used, then the resistance to ground becomes 14.1Ω. This is the steady-state level that the impulse impedance will reach after several microseconds. If we change the number of legs to 6 then R = 15.6Ω. For 4 legs R = 18.7Ω and for 3 legs R = 22Ω.

For a given length of buried conductor, the transient response will reduce to the steady-state minimum resistance faster if the counterpoise is made of several short, radially placed conductors than if it is just one long wire. Figure A-24 shows how the transient impedance of buried conductors varies with several counterpoise configurations.[4] (Widely spaced ground rods cannot attain their ultimate minimum resistance to earth until the current surge reaches the most distant rods.) As a practical matter for counterpoise application, the first 250 feet of buried conductors is the most effective for grounding surge currents. This is brought out by Figure A-24, which shows that a buried counterpoise of four radial elements (L=250 feet per element) will attain an assumed impedance of 10 ohms in less than 2 microseconds. The same length of conductor arranged as a three-element counterpoise will attain the same impedance, but in a time of 2.5 microseconds. Corresponding times for two radial elements and a single element counterpoise are 4 microseconds respectively. Assuming soil of the same resistivity, a greater length of counterpoise conductor buried deeper than the counterpoise of this example would produce lower ultimate effective impedances.

Ground resistance decreases with increasing current in buried conductors if the voltage breakdown gradient of the soil is reached and the soil ionizes. The proportional reduction in resistance from a soil ionization is less for grounds of low resistance than for grounds of high

resistance. Figure A-25 shows typical measured values of ground resistance as a function of various impulse currents.

From the foregoing characteristics of impulse grounds we see that the greater the number of legs, the lower (almost directly proportional) the peak impulse impedance. As a result, the lowest impulse impedance ground system would be obtained by using a buried mesh or solid-metal grid connected at the center. The diameter of the grid should be large enough, considering soil propagation constants, to attenuate end reflections and delay arrival of the reflection a sufficient time so that the NEMP pulse at the point of connection would decay considerably before the reflection returns. The greater the ground losses, the smaller the impulse ground diameter can be. The attenuation effect on the impulse current from earth resistivity and distance of travel from the connection point along the impulse ground can be seen in Figure A-26.

A-11.2 Measurement of Soil Resistivity

One of the requirements for a good grounding system in an NEMP environment entails knowledge of the local soil resistivity. Resistivity will be a determining factor in establishing a low-impulse impedance current path from the shielded facility to ground. Impulse impedance is approximately proportional to the inverse square root of the soil conductivity.

Soil resistivity can be adequately measured by the four pole method. In this method four ground rods are used; the outer two are driven by a current sour and the inner two are used as voltmeter terminals for a high-impedance voltmeter. This constitutes a four-terminal resistor, the resistance of which depends upon the distance between the electrodes and the soil resistivity. When resistivity is being measured, low-frequency AC should be used as a source to avoid DC earth polarization. In this way, soil resistivity can be measured over a region whose linear dimensions are about the same magnitude as the distance between the rods (or electrodes). For an impulse ground, only the resistivity of soil in the general area in contact with and surrounding the counterpoise will determine the impedance. As a result, it should be sufficient to determine the surface layer resistivity to a depth approximately equal to twice the burial depth and approaching the counterpoise diameter.

Typical earth resistivity for various soil types are shown in Table A-VI. Soils generally vary from 10 to 10,000 meter-ohms for good to poor soils; however, much greater variations are possible (for example, basalt can be as great at 10^9 meter-ohms).

A-12.0 EFFECTS OF PENETRATIONS AND OPENINGS ON SHIELDING EFFECTIVENESS

A-12.1 Doors and Air Ducts

Typical openings in shielding for doorways, ventilators, exhaust and intake openings as shown in Figure A-27 will reduce the attenuation

TABLE A-VI

Representative Values of Earth Resistivity

MATERIAL	TYPE	APPROXIMATE RESISTIVITY RANGE, METER-OHMS
Soil	Good	10-100
	Average	100-1000
	Poor	1000-10,000
Seawater	--	0.2-0.25
Freshwater	--	10^3-10^4
	Marine Sands & Shales	1-10
	Marine Sandstones	1-100
	Clay	10-100
Sediments	Sandstone (Wet)	10^2-10^4
	Sandstone (Dry)	10^4-10^7
	Limestone	10^4-10^8
Igneous	Granite	10^3-10^9
Rock	Basalt	10^5-10^9
	Slate	10^3-10^5
	Marble	10^3-10^8
Metamorphic Rock	Gneiss	10^3-10^7
	Serpentine	10^3-10^7

of a room or building in the vicinity of the opening. Figure A-28 shows the attenuation to be expected at a distance (Y) from an opening with the largest dimension of the opening given as W. This family of curves is to be used for values of Y/W which result in attenuations equal to or less than the center-area attenuation calculated for a shielded room or enclosure.[3,5,17]

To increase the attenuation near an opening, a metal sleeve (wave guide) extending out of the room can be installed which will result in attenuation equal to the center-area attenuation of the room.[12] To determine the sleeve size, use the largest dimensions of the opening as the value D on the wave guide graph (Figure A-29). After determining the attenuation desired, find the length of sleeve required (L) from the appropriate curve.

An example of the use of the opening attenuation curves is as follows: Assume a shielded room having a center-area attenuation of 20 decibels. A doorway into the room is 8 feet high and 3 feet wide. The largest opening dimension is the doorway height of 8 feet. From Figure A-28 the curve which becomes asymptotic to the center-area attenuation (20 decibels) gives a Y/W ratio of approximately 3:1. At a distance Y from the doorway, where Y=3W=3x8=24 feet, the attenuation will be the same as the center area of the room. For equipment located closer to the doorway, the attenuation will be less, as shown in Figure A-28. If equipment is 4 feet away from the doorway, the ratio Y/W = 0.5, and from the graph the attenuation there would be about 10 decibels.

To reduce the penetration of the H-Field at the opening, a metal wave guide or tunnel (vestibule) should be installed at the opening. With the same 8 foot opening as used for the doorway, the largest wave guide dimension will also be 8 feet. With D=8 feet (2.4 meters) and a center-area attenuation of 20 decibels required, the length of the wave guide (L) is found from Figure A-27 to be 1.8 meters, or 6 feet. Thus, a wave guide entrance of the dimensions calculated above can reduce the H-Field by 20 decibels in the doorway and still maintain the same level of center-area attenuation in the room (Figure A-30).

Cables to be brought into an NEMP hardened shelter can make use of the conduit penetrations shown in Figures A-31 and A-32. These penetrations are for rebar, wire mesh, and solid steel plate shielding techniques. Recommended methods for attaching suitable flanges to penetrating conduit and pipe are shown in Figure A-33.

A-12.2 Cable Conduits

For cable runs external to shielded instrumentation centers, a continuous metal conduit surrounding the cable will provide maximum shielding against NEMP fields. Properly installed continuous steel conduits, with 1/4 to 3/3 inch wall thickness will, in general, reduce high electromagnetic fields and the resulting induced cable currents to a level at which most typical circuits will not be disrupted.[18,20]

Voltages induced on conductors within conduit have complex wave forms and depend upon a number of factors, including:[17]

1. The current through the conduit produced by the H-Field environment creates a voltage drop through the resistance of the conduit, which can be coupled into contained conductors.

2. The type of conduit material used is a factor. Higher magnitude induced voltages tend to appear on low permeability conduits, such as those made of aluminum rather than on those of high permeability, such as steel.

3. The diameter (trade size) and wall thickness of the conduit are factors. There is less coupling of induced voltages into conductors within large diameter conduits than into small ones; also, induced conductor voltages vary approximately in inverse proportion to the square of the conduit wall thickness.

4. The number and kind of bends influence both magnitude and wave shape of induced voltages on conductors. These induced voltages are directly proportional to the number of bends (Figure A-34). Higher conductor voltages are induced in severe, short-radius bends than in gradual ones. This, in part, is the basis for general avoidance of condulets in conduit assembly. Another reason is that the condulet covers may be accidentally removed or omitted, resulting in extremely high flux leakage into the conduit with consequent increases of voltage induced on the wiring.

5. The number of conduit couplings. Figure A-35 shows that induced conductor voltages are directly proportional to the number of couplings in a conduit run, assuming that all the joints are constructed to a high standard of workmanship. Even one poorly made or loose joint could enormously increase these induced voltages. This supports the requirement of electrically-conducting sealants on threaded couplings or continuous welds at threaded couplings.

6. The length of conduit runs is a factor. Voltages induced on conductors in conduits are directly proportional to conduit length, as indicated in Figure A-34. This dictates the need of careful design to minimize the length of conduit runs.

7. The actual position and arrangement of conduits grouped together in ducts or trenches between buildings is a factor. Experimental and analytical results of several conduit grouping arrangements have indicated that the H-Field induced current will divide between the individual conduits within the group with the higher current being carried by the outermost conduits in the group.[17] This suggests that, wherever possible, the power wiring should be run in the outermost conduits in a group and signal wiring should be run in the innermost conduits.

When conduits are run in groups, the resulting current division, in effect, reduces the induced voltage on the wiring within these conduits.

The induced voltage from wiring within a conduit for given conduit currents as determined by the nomograph, Figure A-36, can be obtained from Figures A-34 and A-37. To determine the value of current to use for Figures A-34 and A-37, when conduits are run in a group, refer to Figure A-38. The multiplying factors given in Figure A-38 are conservative.

8. The types of conductors within the conduit are important. Because of the greater area presented to EMP flux leaking into the conduit, voltages induced on parallel pairs will generally be higher than on twisted pairs (Figures A-34 and A-35). Cables constructed with wound or braided shields within conduit are very effective in reducing the induced voltages, provided such shields are properly grounded.

9. The actual position of conductors within conduits is a factor. This also affects the induced voltages, but this factor is beyond control by design; only random positions can be assumed.

A-13.0 TEST PROCEDURES

A-13.1 Test Procedures for Shielded Rooms[17]

The recommended technique for testing the attenuation of shielded rooms and shielded equipment enclosures is based on a proposed IEEE standard.

This test is particularly adaptable to rectangular enclosures with edge dimensions of five to fifty feet and can be conducted after the enclosures are installed with all penetrations, openings, and equipment in place. The test instruments required are largely conventional and can be hand-carried to the test location.

The basic set-up for a shielded enclosure test is shown in Figure A-39. The magnetic field is generated by RF current through a large planar loop of wire encircling the enclosure, spaced by insulating blocks at least one inch away from the outer shielding surfaces. The loop, consisting of a single turn of insulated #18AWG stranded copper wire, should be oriented at an angle to all enclosure surfaces as shown.

The amplified output of any stable, continuous wave RF source, such as an oscillator may be used to excite the loop. Generally, the amplifier output impedance is selected to match the loop impedance. The loop current should be monitored by a suitable RF ammeter or by measuring the voltage drop across a known carbon resistor in series with a loop supply lead.

The sensing loop diameter and number of turns will be governed by the sensitivity of the available detection equipment and by the available space within the enclosure for changing sensing loop positions.

Either conventional field strength meters or RF voltmeters capable of resolving 300 microvolts are suitable as detectors.

When making an evaluation of shielding attenuation the following procedure is required.

1. Install the exciting loop and set up the test equipment as shown in Figure A-39.

2. Extend the shielded leads from the sensing loop outside the enclosure to the detection device.

3. Initially mount the sensing loop in the same plane as the exciting loop and as close to it as possible.

4. Energize the exciting loop and the detector and adjust the excitation current until a measurable readout is observed at the detector.

5. While maintaining the frequency and the magnitude of the current through the exciting loop, successively reposition and reorient the sensing loop within the enclosure until a maximum reading is obtained. Record this maximum reading and its location.

6. Accurately measure the dimensions of the exciting loop while in place on the enclosure. Then remove the loop and set it up, preferably in a horizontal plane in an area clear of nearby objects.

7. Mount the sensing loop in the exact center of the exciting loop and align it to be in the same plane as the exciting loop.

8. Reconnect the leads to both loops and again energize the exciting loop.

9. Read and record the magnitude of the field strength or voltage coupled into the sensing loop without shielding.

10. Evaluate the shielding attenuation. Determine the shielding ratio by dividing the unshielded quantity read in Step 9 by the maximum shielded quantity read in Step 5. Then:

$$\text{dB} = 20 \log_{10} \frac{\text{RF voltage unshielded}}{\text{RF voltage shielded}}$$

11. Compare the shielding attenuation with minimum required levels. If the requirements are not met, the defects must be located and corrected.

A-13.2 Conduit Discontinuity Detection Tests[17]

The basic test set-up for detection of conduit discontinuities is shown in Figure A-40. The test locates and evaluates flaws in conduits and fittings or defective joints and discontinuities that would result in an attenuation loss or shielding degradation with high intensity ambient fields and currents.

This test set-up requires that a special insulated number 16AWG "sense" wire be permanently installed in each conduit as shown in Figure A-40. The test consists of circulating a 500 KHz current in the conduit by means of a portable test set which includes the RF source, current inducing probe to couple current onto the conduit, current transformer to measure the conduit current, and an RF voltmeter to measure the voltage induced in the sense wire.

When making a conduit test, the following procedure is recommended:

1. Remove the grounding device at one terminal of the sensing circuit.

2. Check the sensing circuit for continuity using an ohmeter or buzzer set.

3. If the sensing circuit is intact, connect it to the RF voltmeter.

4. Circulate a 500 KHz high frequency current through the conduit and measure its amplitude.

5. While maintaining the test current, read and record the voltage induced in the sensing wire.

6. Calculate the ratio of millivolts induced in the sensing wire to amperes circulated through the conduit on test.

7. In general, intact conduits, regardless of length or trade size, will not test more than ten millivolts per ampere at a frequency of 500 KHz. Values in excess of 10mV/A @ 500 KHz, are indicative of conduit defects and maintenance service should be scheduled on the conduits in question.

Although the criterion for acceptable conduit conditions has been determined as equal or less than 10mV/A @ 500 KHz, this should not be taken to mean that high frequency currents on the order of amperes need be circulated. Actually, the test is as feasible for high circulating currents with relatively insensitive detection systems as it is for moderate circulating currents (order of milliamperes) with reasonably sensitive detection systems.

A-13.3 Quick Shielding Leak Detection Method

A rapid means of detecting potential shielding leaks during and after the completion of construction is available with the use of an inexpensive device, the Government Model TS-14 Shielded Enclosure Leak Detection System ("Sniffer"). It consists of a signal source of approximately 95 KHz modulated at 1000 Hz, which is connected through attachment leads to diagonally opposite and outside corners of a shielded enclosure. The source driving circuit is series resonated with a variable capacitor to provide maximum current through the shielded enclosure. The output power ranges from 1.6 to 16 watts peak. A separate small hand held and battery supplied receiver with speaker, ten step attenuator and meter indication calibrated in dB's and with a long insulated rod containing a ferrite loop probe is then used to probe suspect seams, holes, closures, etc. The receiver has about 140 dB dynamic range. Attempts were made to correlate resultant measurements with MIL-STD-285 shielding effectiveness measurements at 400 MHz and 1 GHz.[20] The authors of this technical note do not recommend the use of such correlated measurements in lieu of regular MIL-STD-285 measurements, but find the "Sniffer" a very sensitive and very useful tool for finding points of leakage.

A-14.0 CHOKE CORES FOR COMMUNICATION CABLES

Current entering the sites on the communication lines appears to be a serious problem. These cables are shielded and are buried external to the sites. Typically, the cables enter the site through a sleeve in the basement wall and then run upstairs to the various equipment floors. On some sites the cables go directly to the various floors; on others they terminate at a telephone distributor frame in the basement. The worst offenders would be those cables going directly to the equipment floors. Currents injected externally on the cable shield would flow all the way up to the equipment floors before being taken off onto a ground wire and then would flow all the way back down to the site ground. Thus, the currents would set up the maximum electromagnetic fields in the site.

A-14.1 Effect of Grounding Cable Shields

Where these problems have been encountered, recommendations have been made to ground the cable shields as soon as they enter the site. The degree to which grounding connections divert current off the cable shield onto the grounding system depends on the impedances of the grounding connections and the cable shield. Figure A-41a shows a cable grounded as it enters the site. Figure A-41b shows the equivalent electrical schematic. L_g and L_c represent, respectively, the inductances of the cable grounding strap and the cable shield plus the tower ground cable. Strictly speaking, these should be surge impedances instead of inductances.

However, if the cable lengths are short compared to the wave lengths of the incoming surges, the problem can be treated in terms of lumped inductances. The current divides inversely as the inductances. Hence, to make i_c small compared to i_g, the ground inductance, L_g, should be small compared to the cable inductance, L_c. Ideally, L_g should be zero, but this is impossible.

The current flowing along the cable can be minimized by grounding the cable shield at several points as shown on Figure A-42. Again, the greater the ratio of cable inductance to ground inductance, the lower will be the current on the cable shield. This suggests that the cable current can be minimized by increasing the cable inductance.

A-14.2 Effect of Magnetic Cores on Cables

Figure A-43 shows how magnetic cores can be placed around the cable to increase the inductance.

Desirable attributes for the cores are:

1. They should be easy to install on existing cables.

2. They should introduce a maximum of inductance into the cable.

3. They should not saturate under the highest cable current.

4. They should be of such nature that flux is not trapped in the core.

5. They should introduce electrical losses for any oscillatory pulse currents flowing on the cable.

Attribute 1 implies that the cores must be split into two parts or otherwise be capable of disassembly.

Attribute 2 implies that each ampere of current through the center of the core must set up a maximum amount of magnetic flux since $L = N (d\phi/di)$. For a given core size this means that the core permeability should be a maximum and the reluctance of the magnetic circuit be as low as possible. These, in turn, imply that the mean circumference of the core must be no more than necessary and that air gaps be held to a minimum. For rapidly changing pulse conditions, high permeability implies that the core laminations should be thin.

These restrictions tend to be at variance with requirements 3, 4, and 5. Minimum air gaps mean that a given cable current carries the core further into saturation. A small air gap introduces some reluctance into the circuit and allows more current to flow before the core saturates. It also allows the core flux to return more nearly to zero when the cur-

rent goes to zero. Thinner laminations have higher permeabilities for short duration pulses, but they cause less hysteresis loss per cycle. In this particular application, high hysteresis loss is desirable. Cores with thin laminations also cost much more than cores with standard 12-mil laminations.

An examination of core characteristics indicates that split toroidal cores of 12-mil lamination thickness will be satisfactory as cable choke coils. A suitable core, assuming it would fit over the communication cables, would be 2.625" I.D., 4.625" O.D. and wound with two-inch wide strips of 12-mil steel (Carstedt catalog No. CRA-17). The manufacturer does not supply catalog information on the B-H characteristics of the split toroids, but these can be estimated from the data supplied for C or U cores. Typical values are:

$$B = 10 \text{ kilogauss at } H = 12 \text{ oersted}$$

$$B \doteq 16 \text{ kilogauss at } H = 33 \text{ oersted}$$

For the above-mentioned core:

1. mean length of magnetic path = $3.625\ \pi$ inches = 29 cm

2. cross section area = $A = 2 \text{ in}^2 = 12.9 \text{ cm}^2$

3. $12 \text{ oersted} = 12\ \frac{\text{gilbert}}{\text{cm}} \times 1.257\ \frac{A \cdot T}{\text{gilbert}} \times 30 \text{ cm} = 452$ ampere turns

4. $\phi = B \cdot A = 10 \text{ kilogauss} \times 12.9 \text{ cm}^2 = 129$ kilolines

$$= 1.29 \times 10^{-3} \text{ weber}$$

5. Assuming the cable only passes through the center of the coil once:

$$L = \frac{d\phi}{di} = \frac{1.29 \times 10^{-3} \text{ weber}}{.452 \times 10^3 \text{ A}} = 2.85\ \mu h$$

A conductor the size of the communication cables has a self inductance of about 1.3 μh per foot. Thus, the addition of one core around the cable is equivalent to an extra 9.5 feet of cable.

The core described would still be in a linear region at a flux density of 10 kilogauss or an excitation of 452 amperes. At an excitation of 600 amperes, the core would start to saturate.

The true division of current depends greatly on the inductance of the ground leads and this is hard to determine. If in Figure A-41 we

assume L_g = 2.5 μh, L_c = 15 μh (cable with five choke cores), and an incoming current, i_i, of 3,000 amperes, i_g would be 2,570 amperes and i_c would be 430 amperes. The cores should not saturate even if the current oscillates and goes beyond 430 amperes. The cable current could be reduced to even lower levels by using choke cores at several points along the cable with intermediate grounding of the cable shield. Suggested installation of choke coils would be as shown on Figure A-44.

A-14.3 Experimental Measurement of Magnetic Characteristics

The magnetic characteristics of the cores depend very much on the characteristics of the gap between the two halves of the core. The magnetic characteristics are best evaluated experimentally. This can be done as shown on Figure A-45. The exciting current, flowing through R_s develops a voltage proportional to the excitation H of the core. The magnetic flux induces a voltage, $V_1 = -N\ (d\phi/dt)$ in the search winding. This voltage is fed to an integrator having the characteristics:

$$V_2 = \frac{1}{RC} \int V_1\, dt$$

Thus, the voltage, V_2, applied to the oscilloscope is equal to:

$$\frac{1}{RC} \int -N \frac{d\phi}{dt}\, dt$$

or,

$$V_2 = \frac{-N}{RC} \phi$$

Figures A-46 and A-47 show hysteresis curves for two split curves. Figure A-46 shows curves for a toroid with four-mil Supersil steel (Carstedt CRH-84-B). Figure A-47 shows curves for a U core of unknown manufacture. In either case the exciting ampere turns necessary for a given flux density are lower than the catalog values used for calculation of the inductance obtainable with the two-inch wide core. The 2.85 μh calculated as obtainable for each two-inch wide core may be pessimistically low. Experiments on the core would resolve the matter.

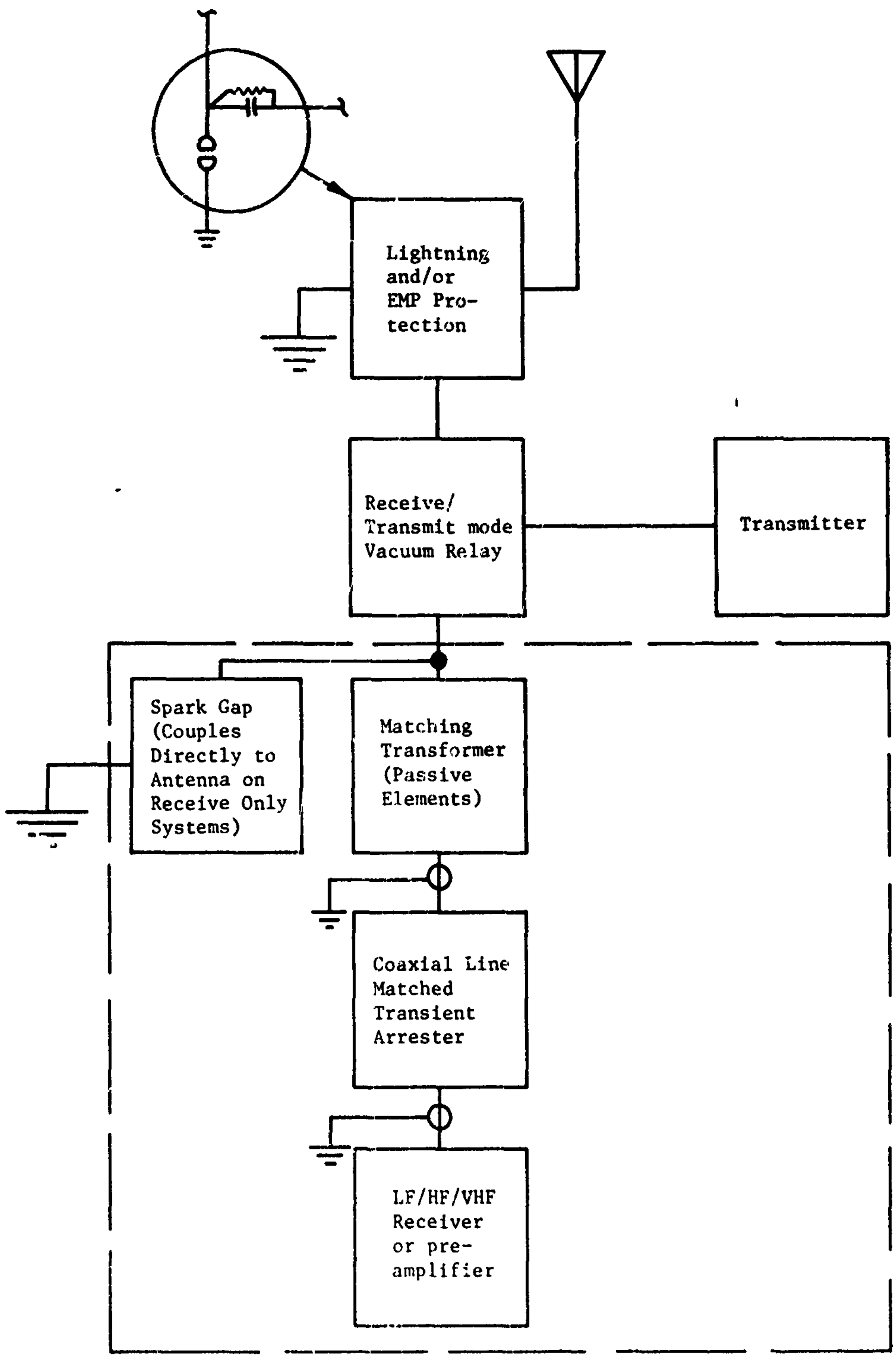


Figure A-1. Protected antenna system block diagram.

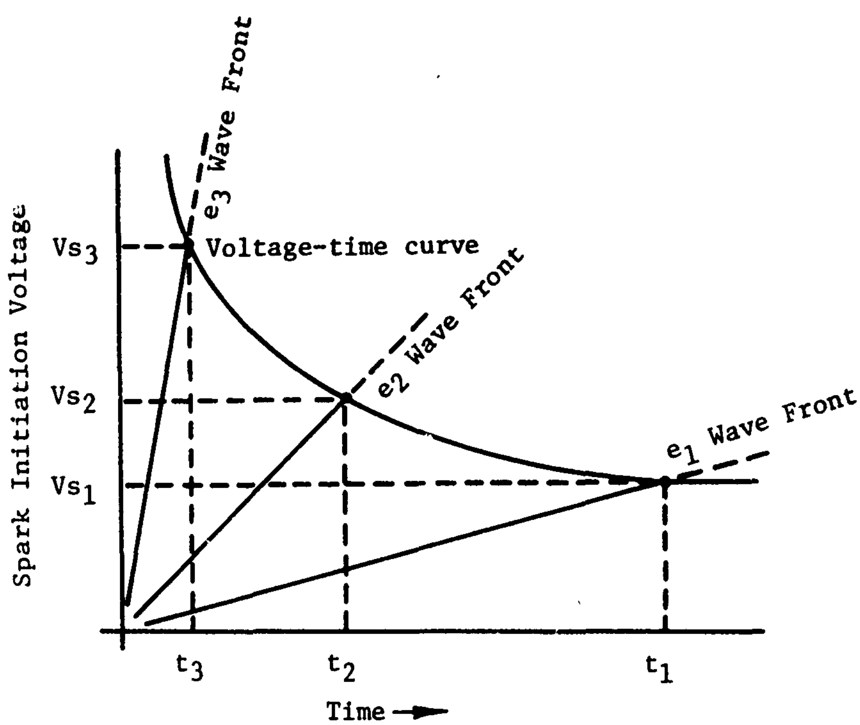


Figure A-2. Typical volt-time curve for spark gaps

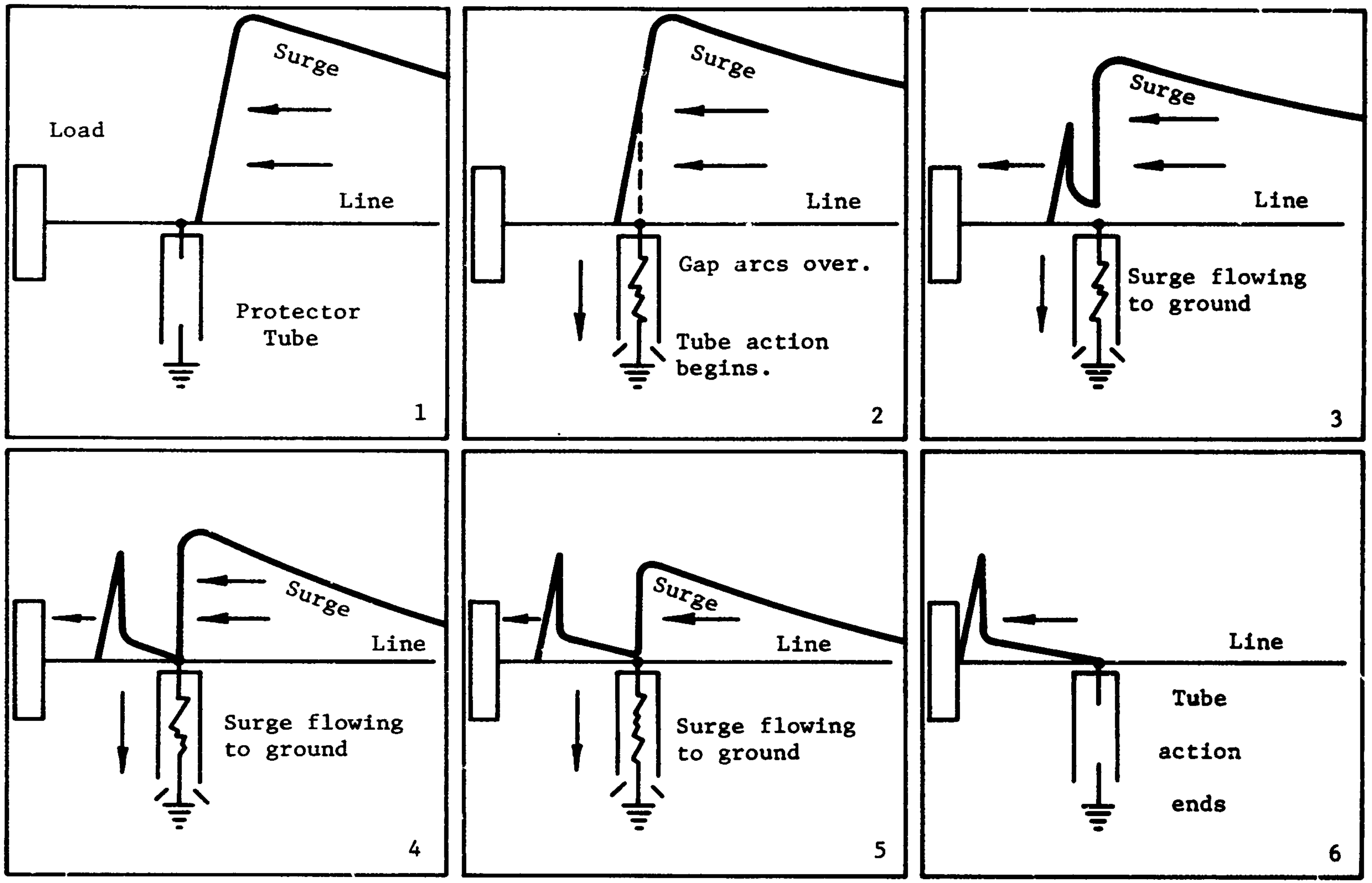


Figure A-3. Sequence of steps in the operation of a typical tube-type arrester.

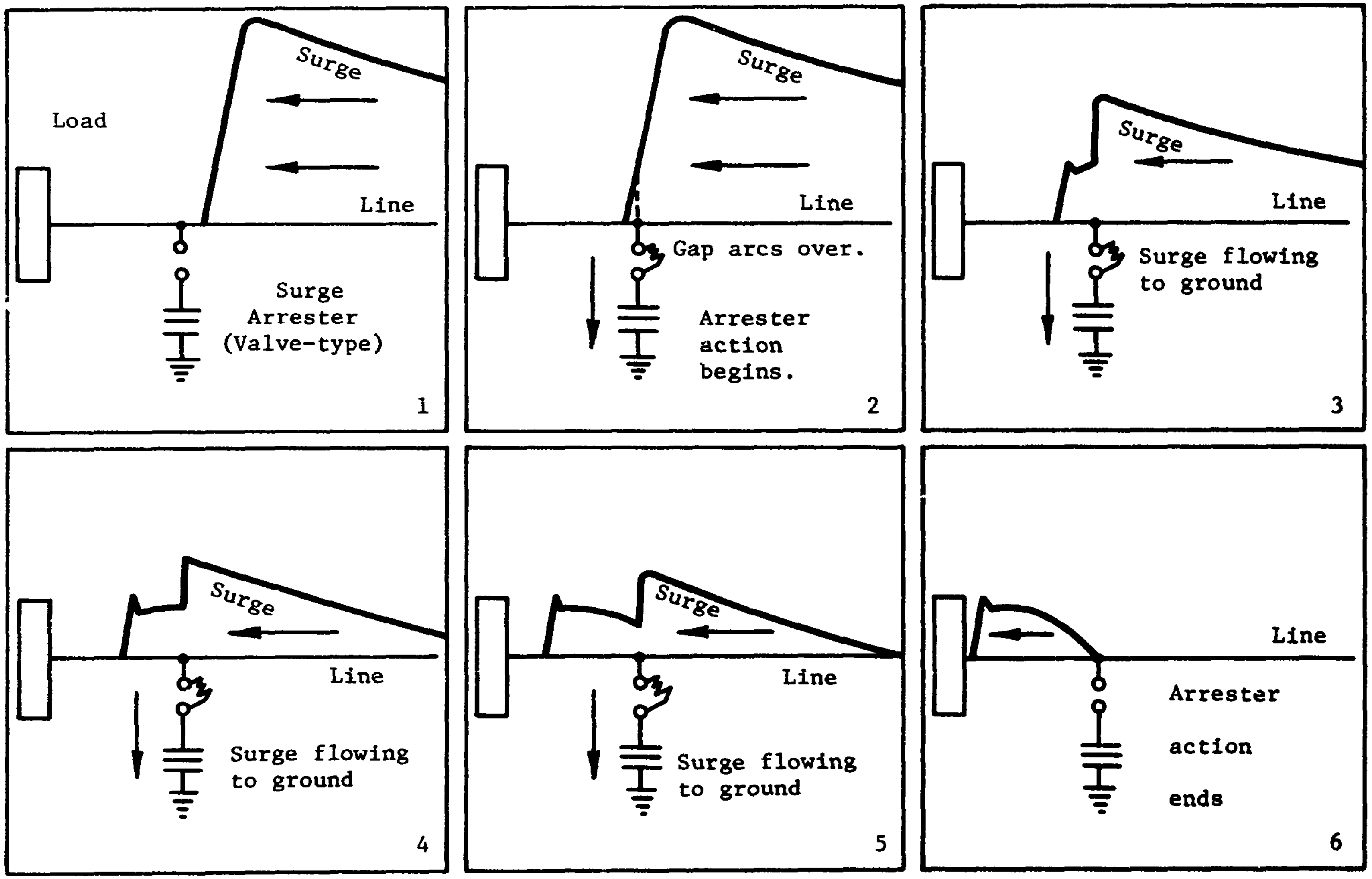


Figure A-4. Sequence of steps in the operation of a typical valve-type arrester.[17]

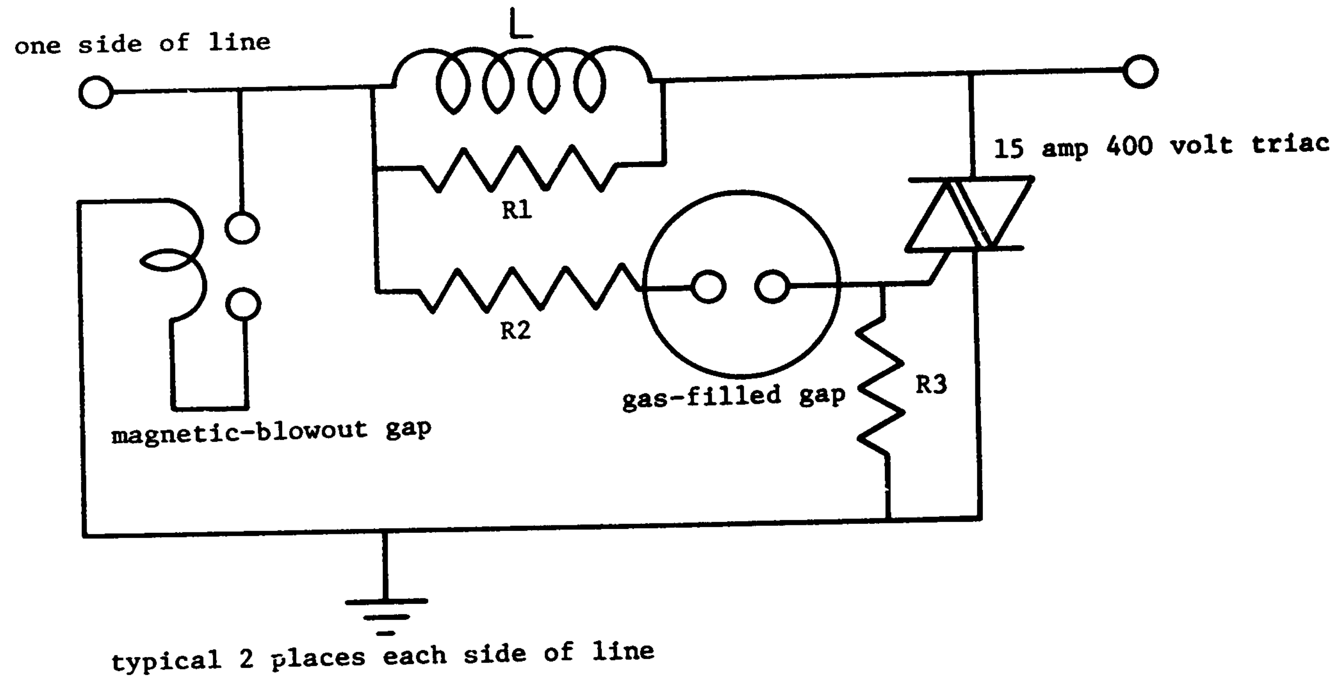
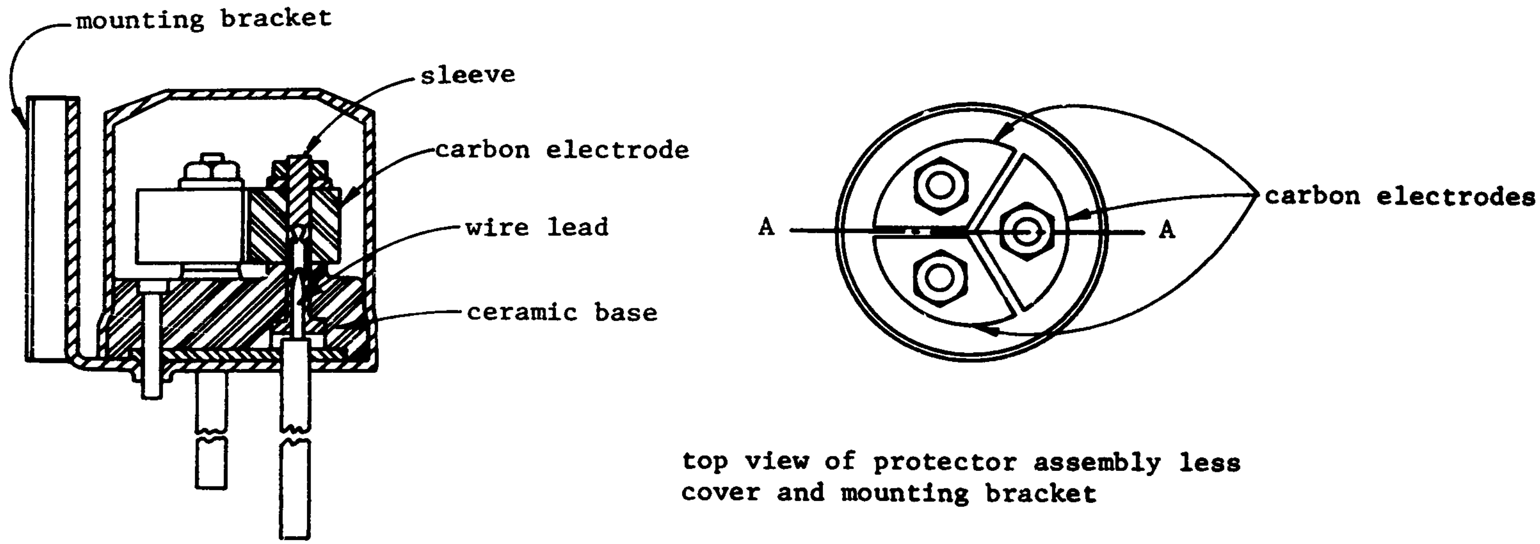


Figure A-5. Example of hybrid AC protector schematic



Section A-A

top view of protector assembly less cover and mounting bracket

Figure A-6. Heavy duty protector in weatherproof mounting.[4]

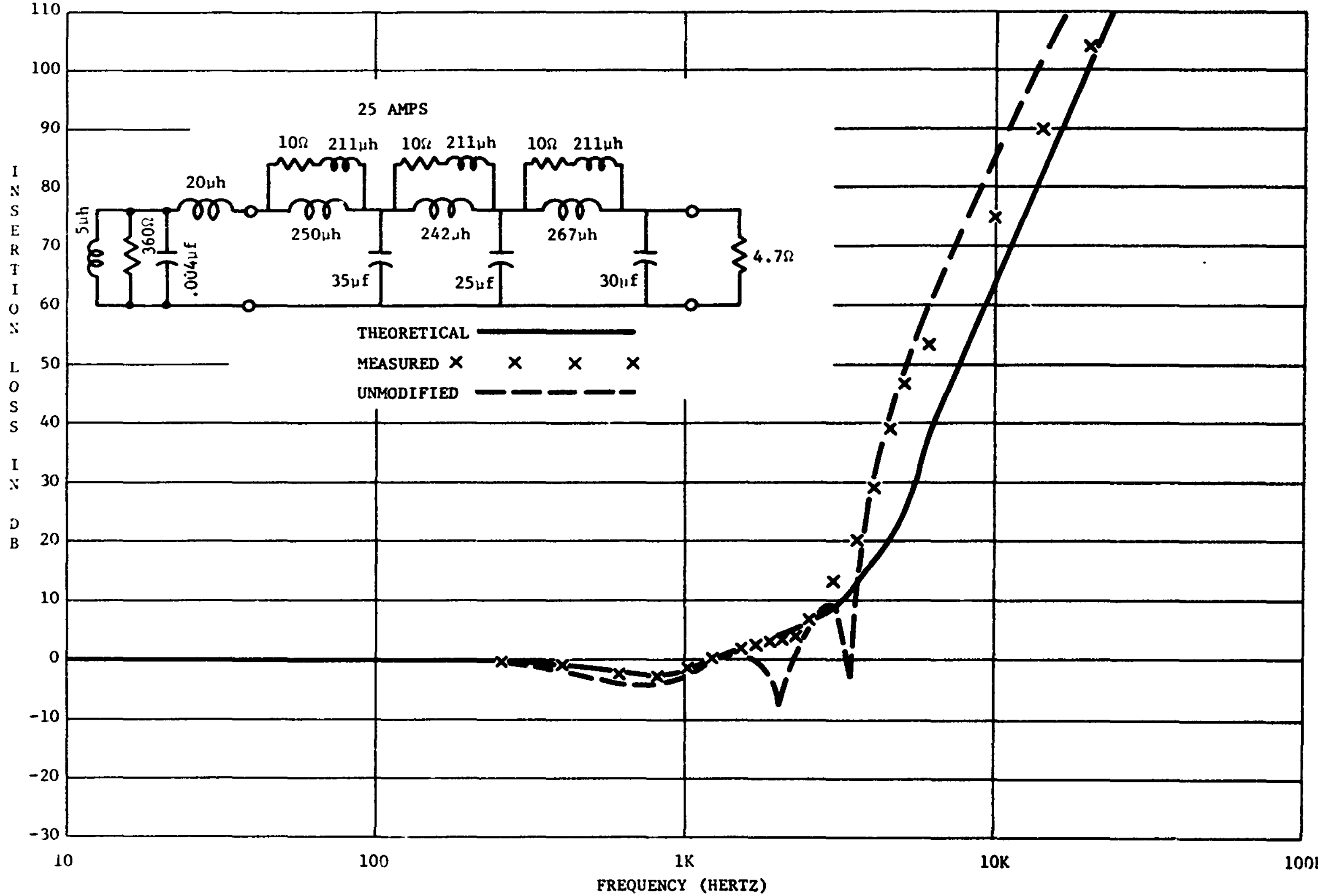
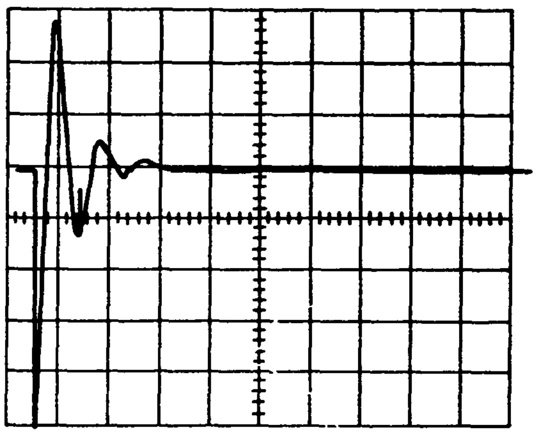


Figure A-7a. Insertion loss curves, Filter G, calculated and measured effects of damping modification.

GF 9355 - MOD B

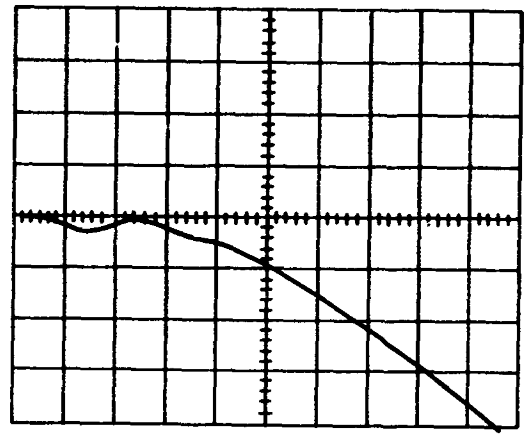
2 AMP LOAD

INPUT WAVEFORM



50 μsec/div, 50 v/div

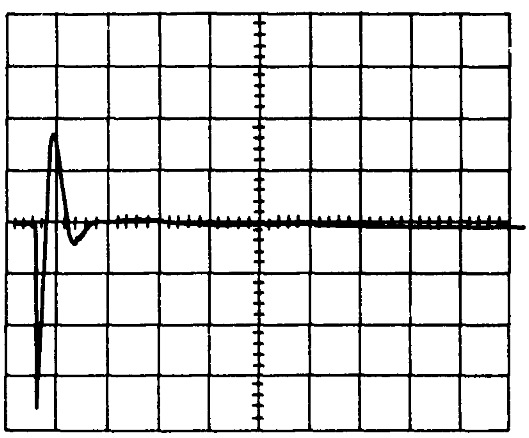
OUTPUT WAVEFORM



200 μsec/div, 10 v/div

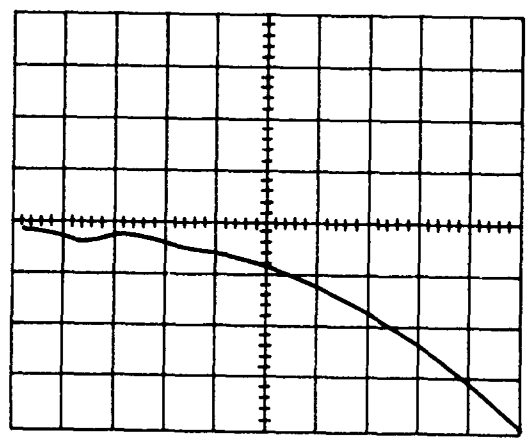
25 AMP LOAD

INPUT WAVEFORM



50 μsec/div, 50 v/div

OUTPUT WAVEFORM



200 μsec/div, 10 v/div

Figure A-7b. Filter G, pulse response.

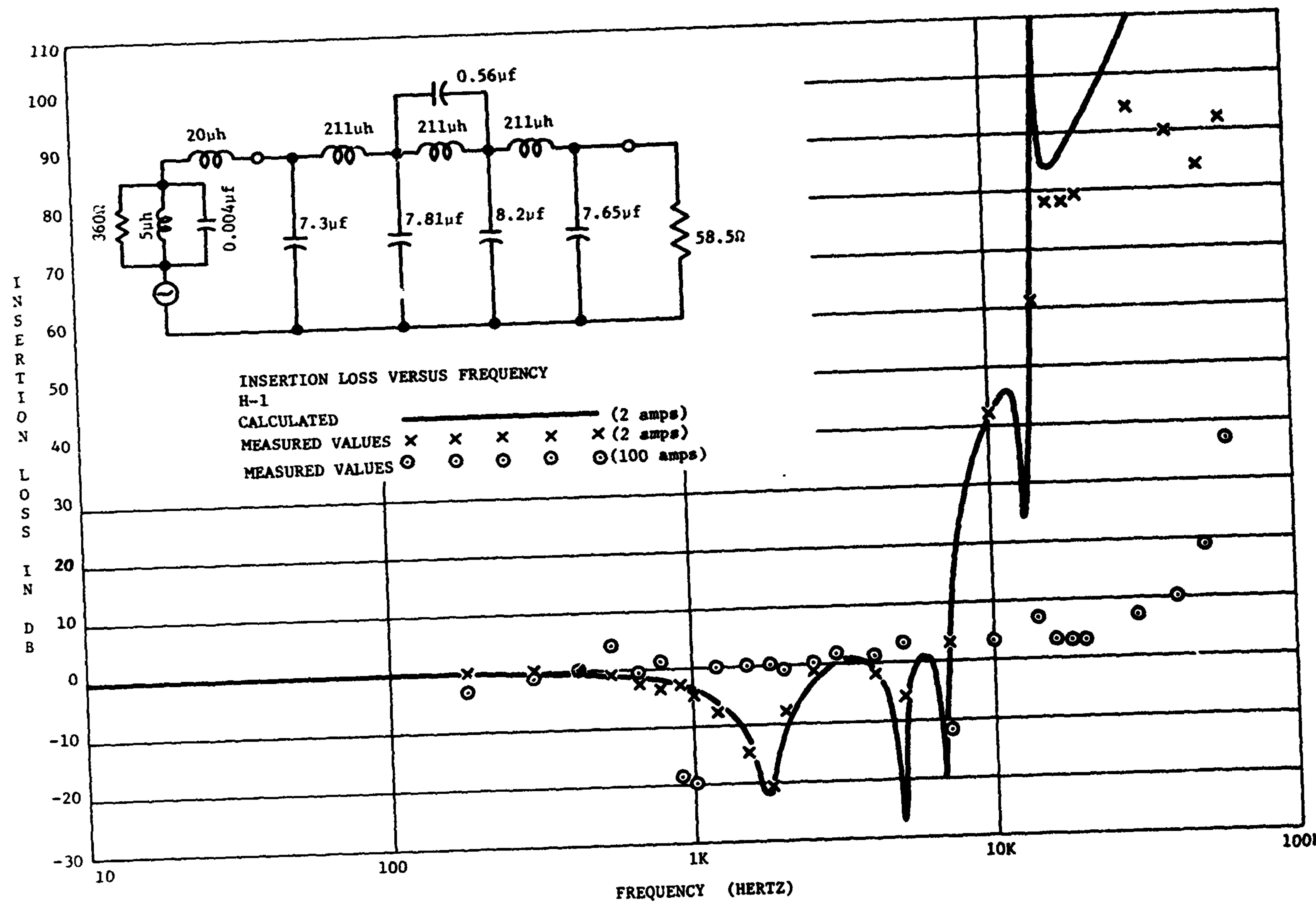
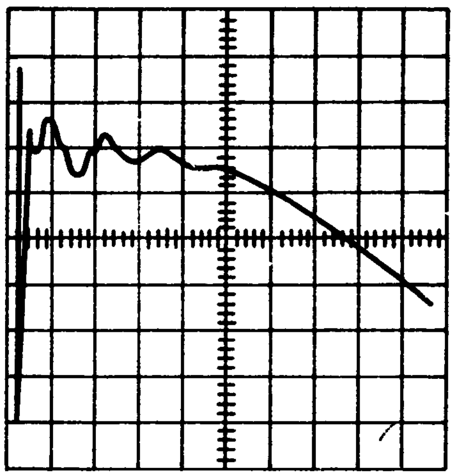


Figure A-8a. Insertion loss curves, calculated and measured, Filter H.

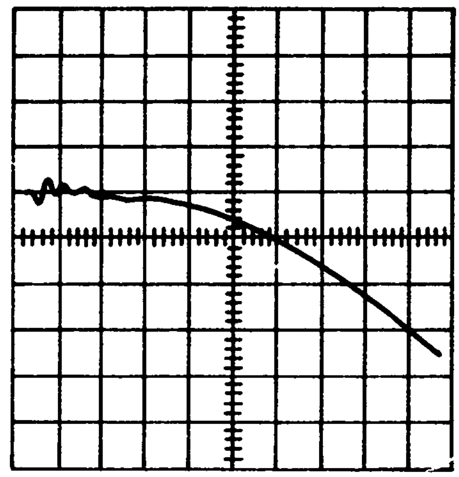
2 AMP LOAD

INPUT WAVEFORM



500 μsec/div, 50 v/div

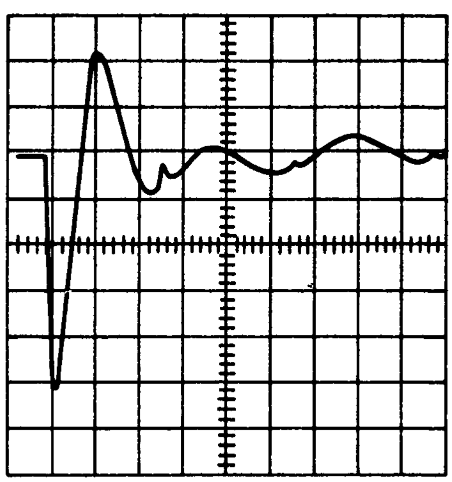
OUTPUT WAVEFORM



500 μsec/div, 50 v/div

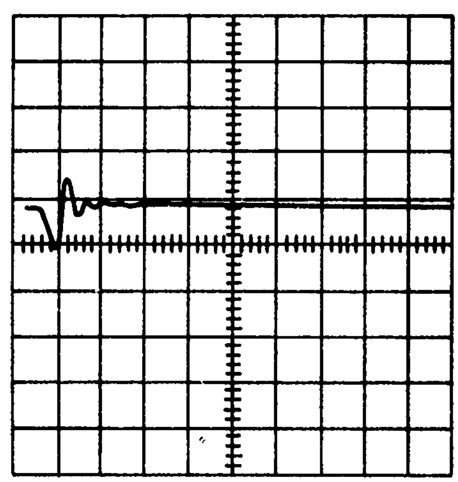
100 AMP LOAD

INPUT WAVEFORM



10 μsec/div, 50 v/div

OUTPUT WAVEFORM



50 μsec/div, 50 v/div

Figure A-8b. Filter H, pulse response.

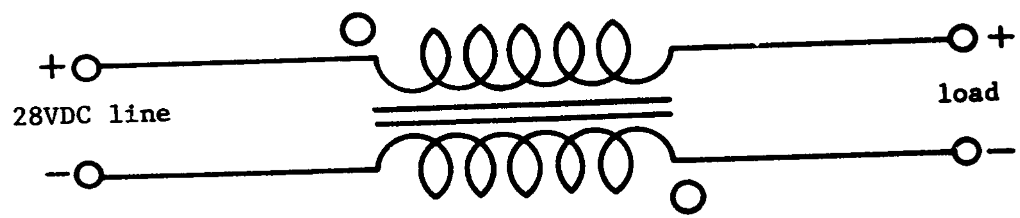


Figure A-9. Transient bucking transformer.

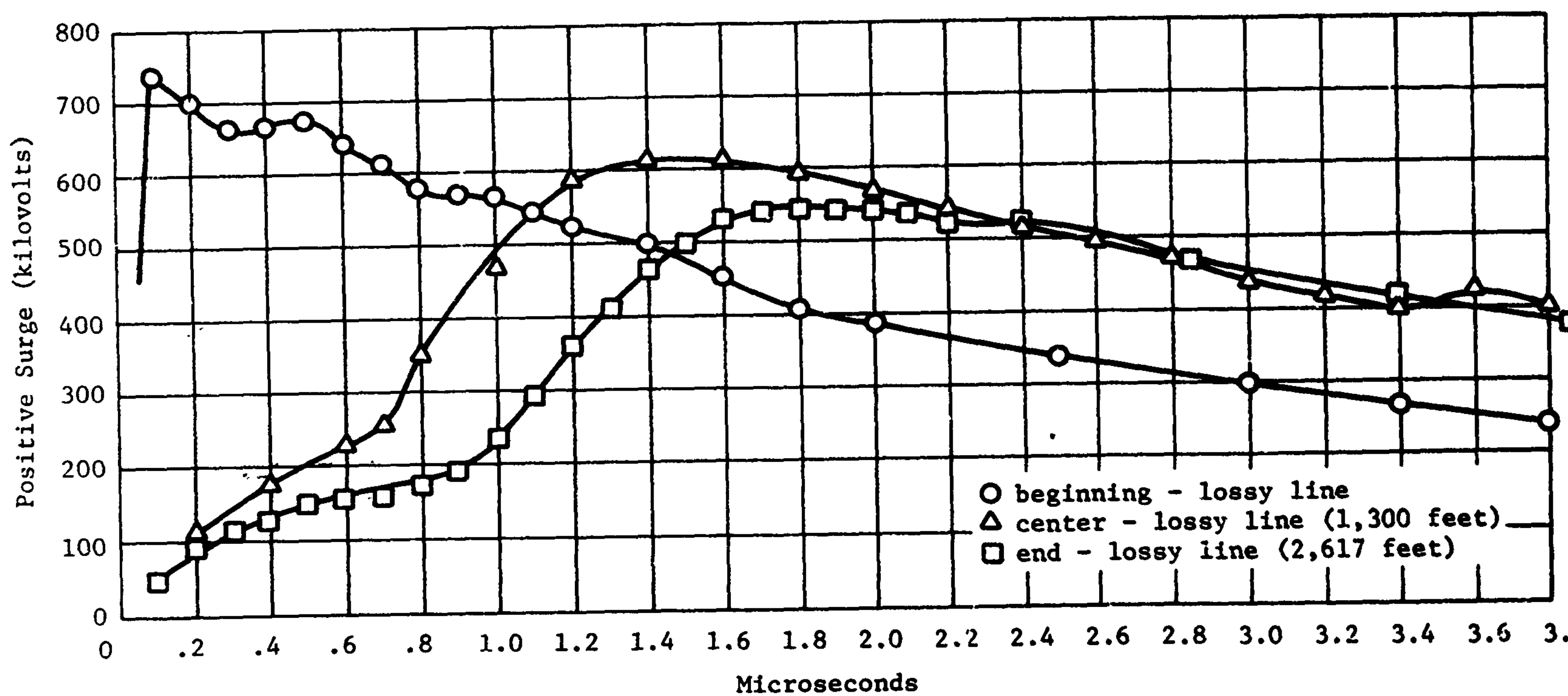
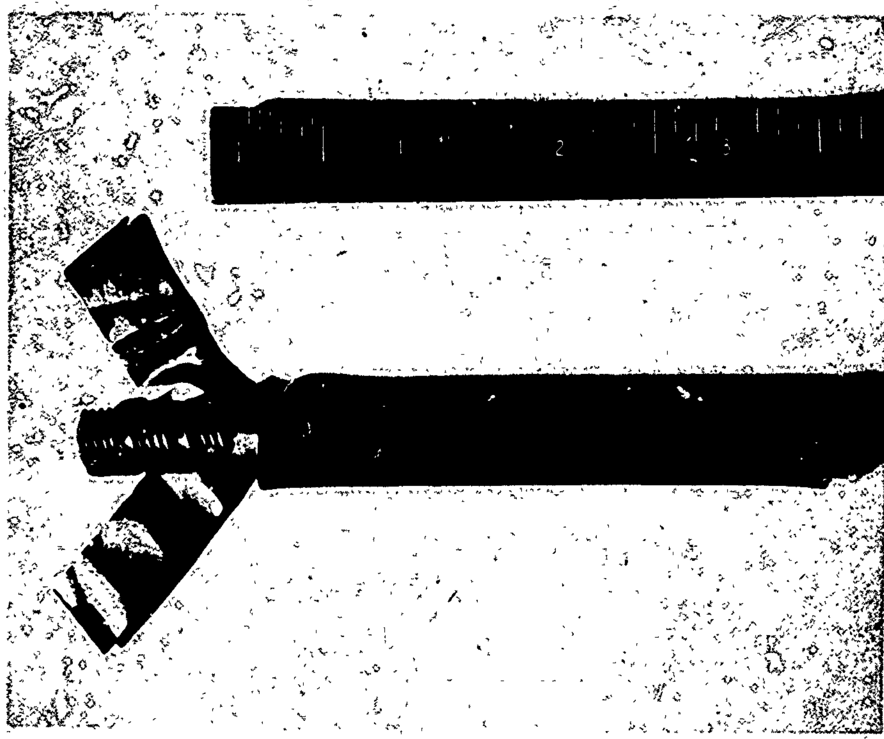
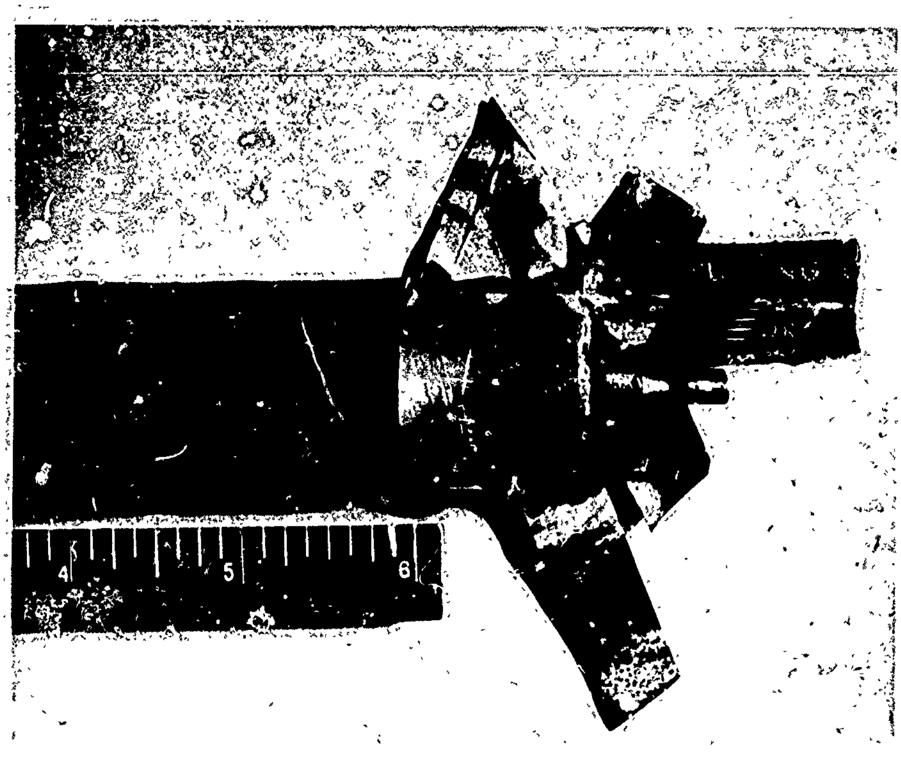


Figure A-10. Voltage wave form on lossy line from high-voltage surge tests.



(a) Overhead line.



(b) Underground cable.

Figure A-11. Photographs of lossy conductors.

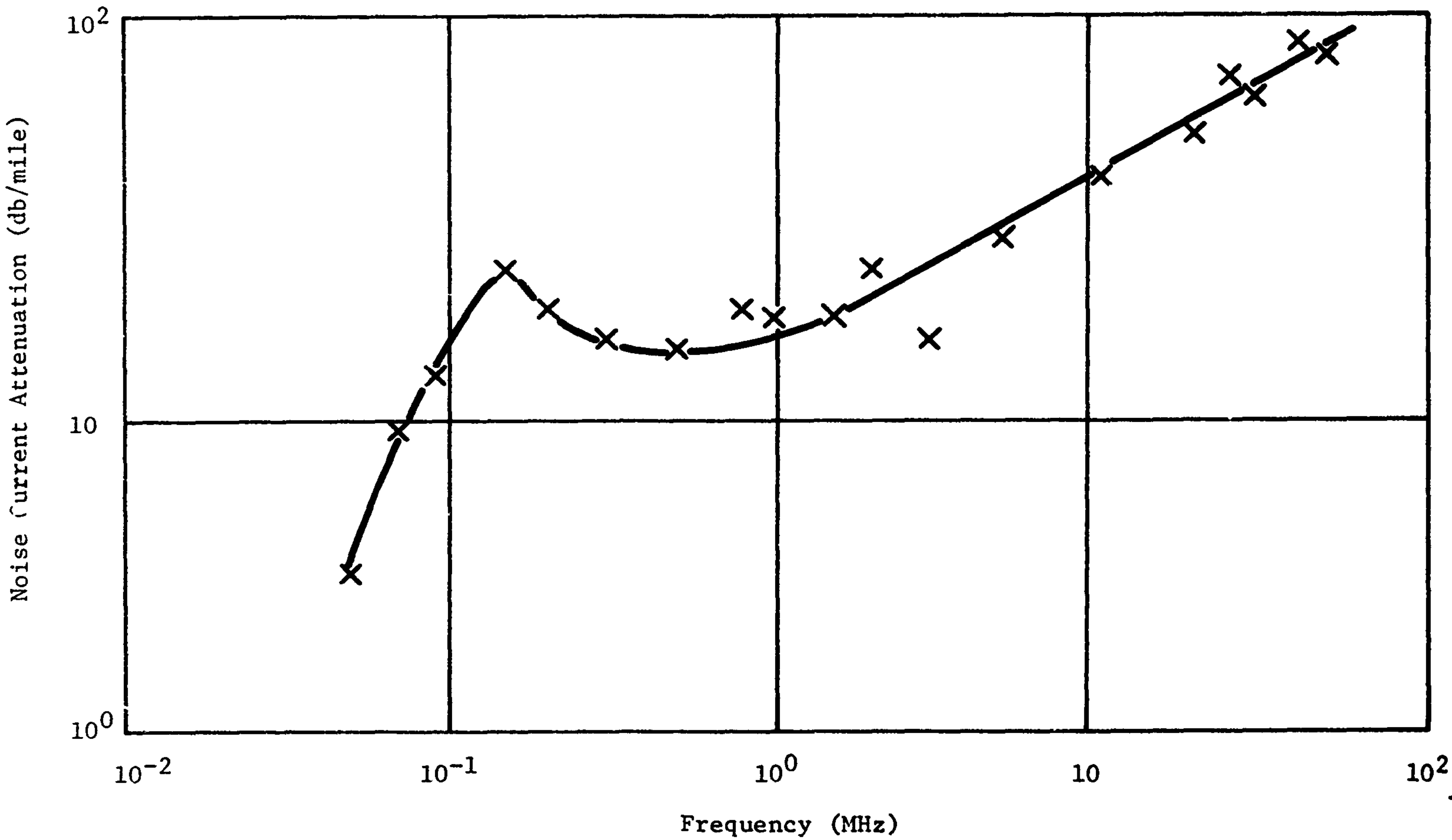


Figure A-12a. Attenuation curve for overhead lossy line, all modes of propagation.[8]

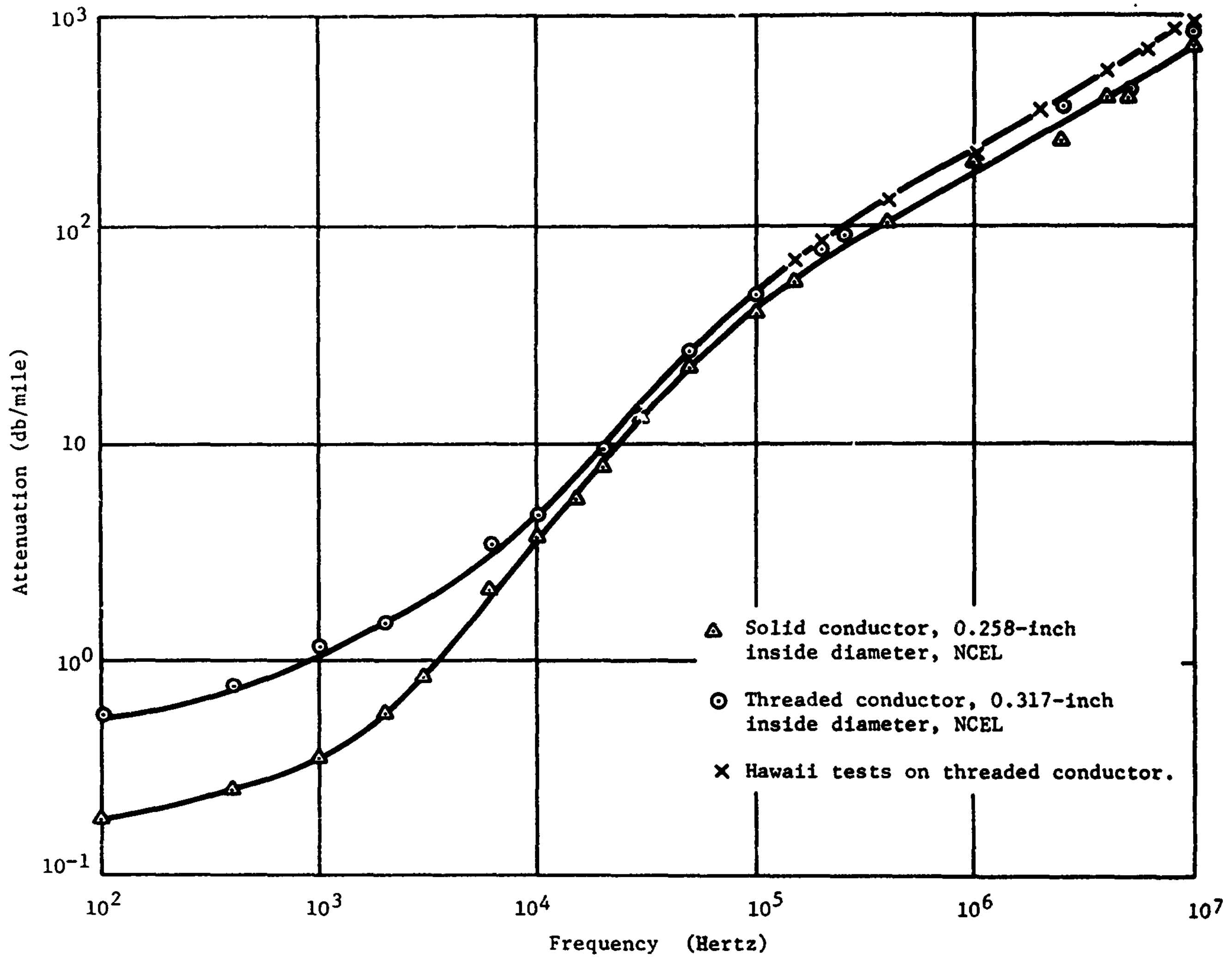


Figure A-12b. Attenuation curves for underground lossy cables with solid and threaded inner conductors.

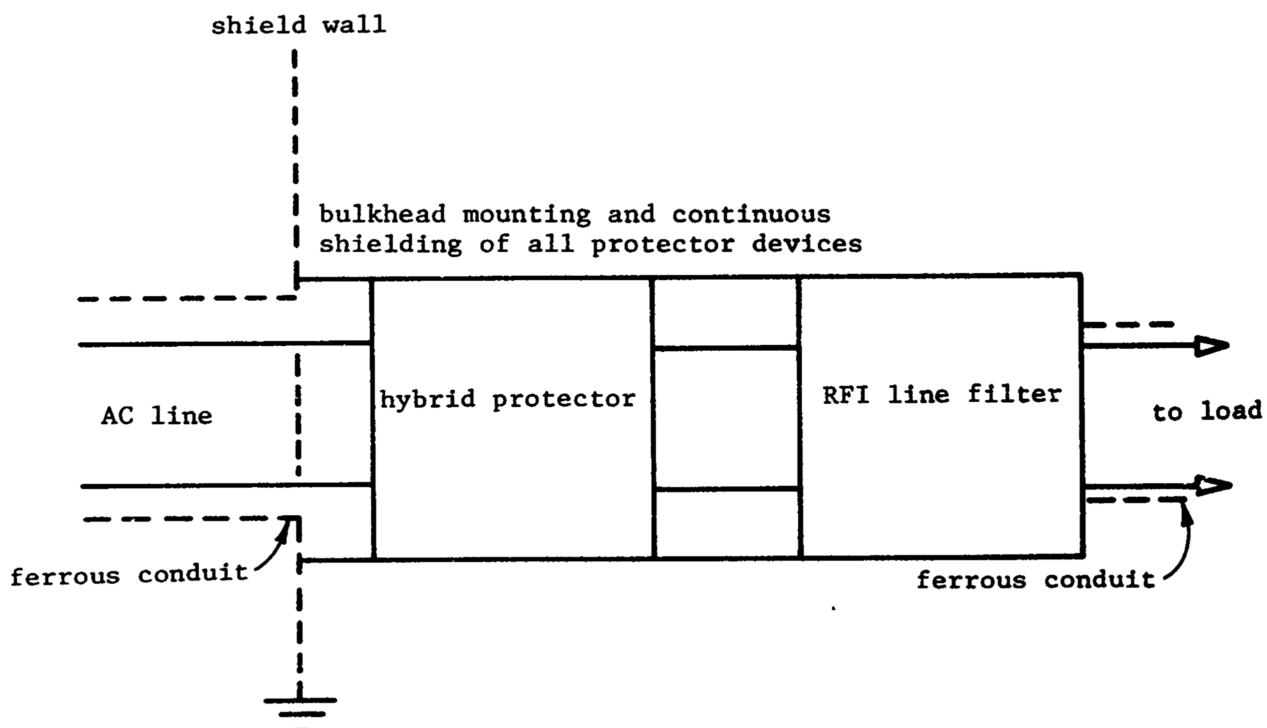


Figure A-13. Example of class four protection for 115VAC line.[6]

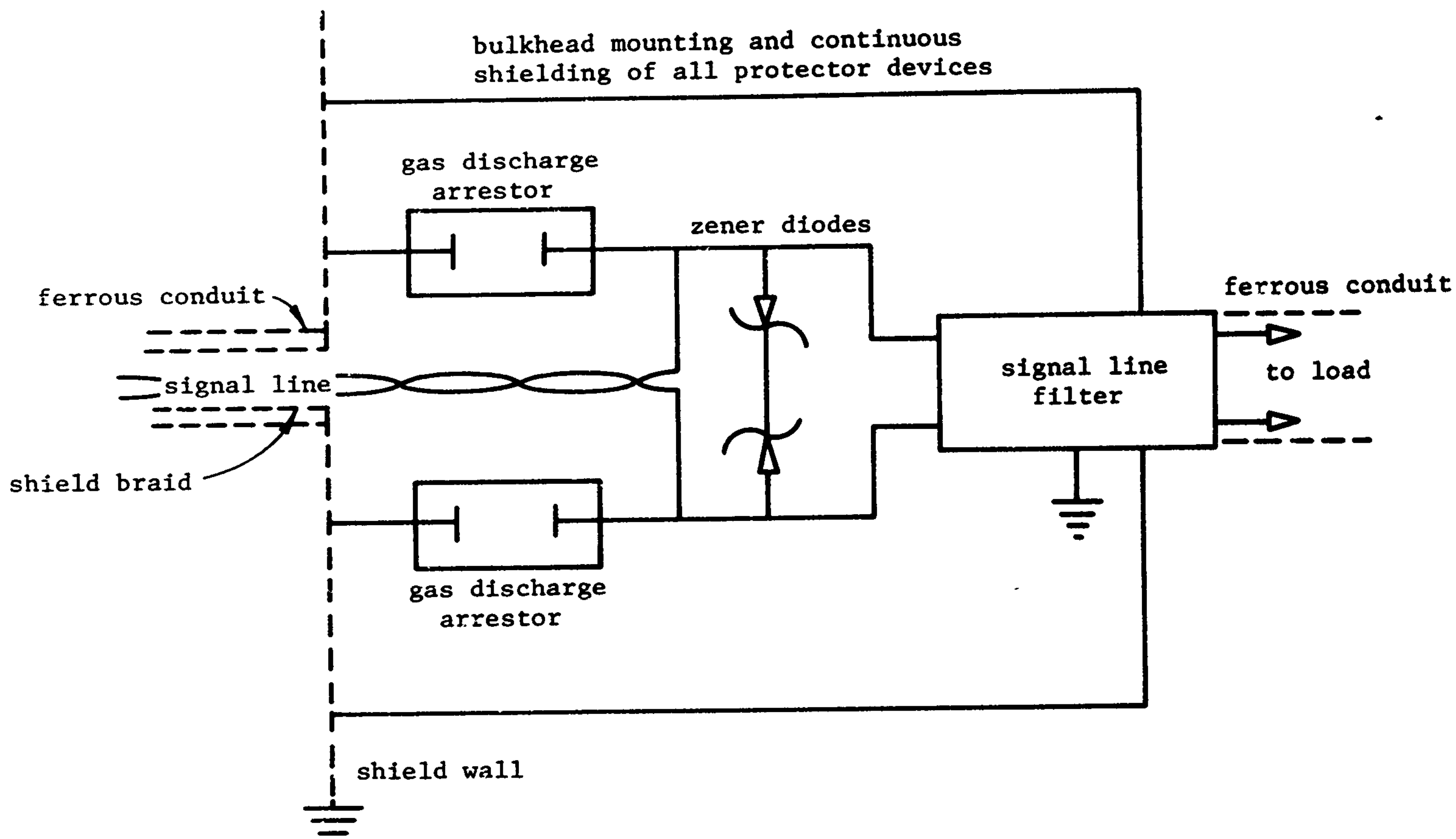


Figure A-14. Example of class four protection for balanced signal line.[6]

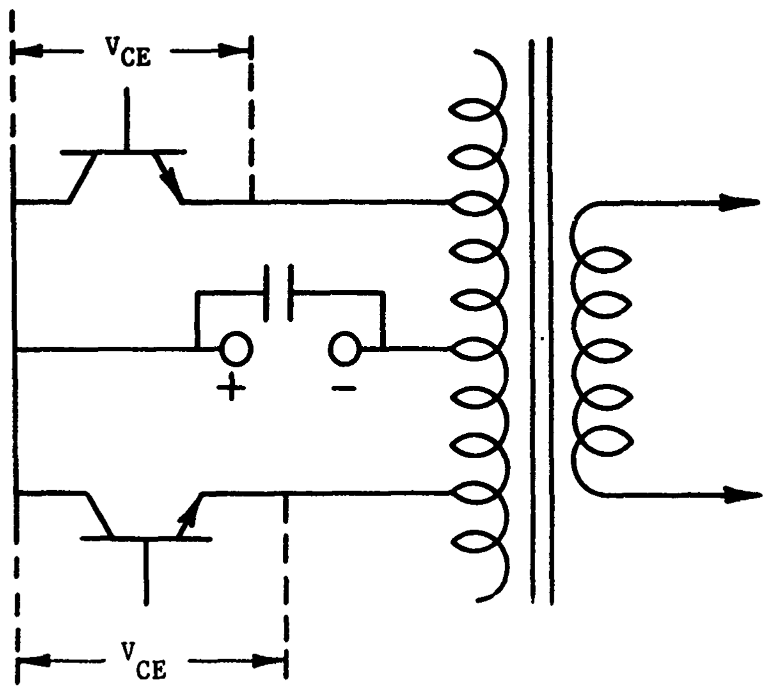


Figure A-15. Typical inverter schematic (base feedback omitted for clarity).

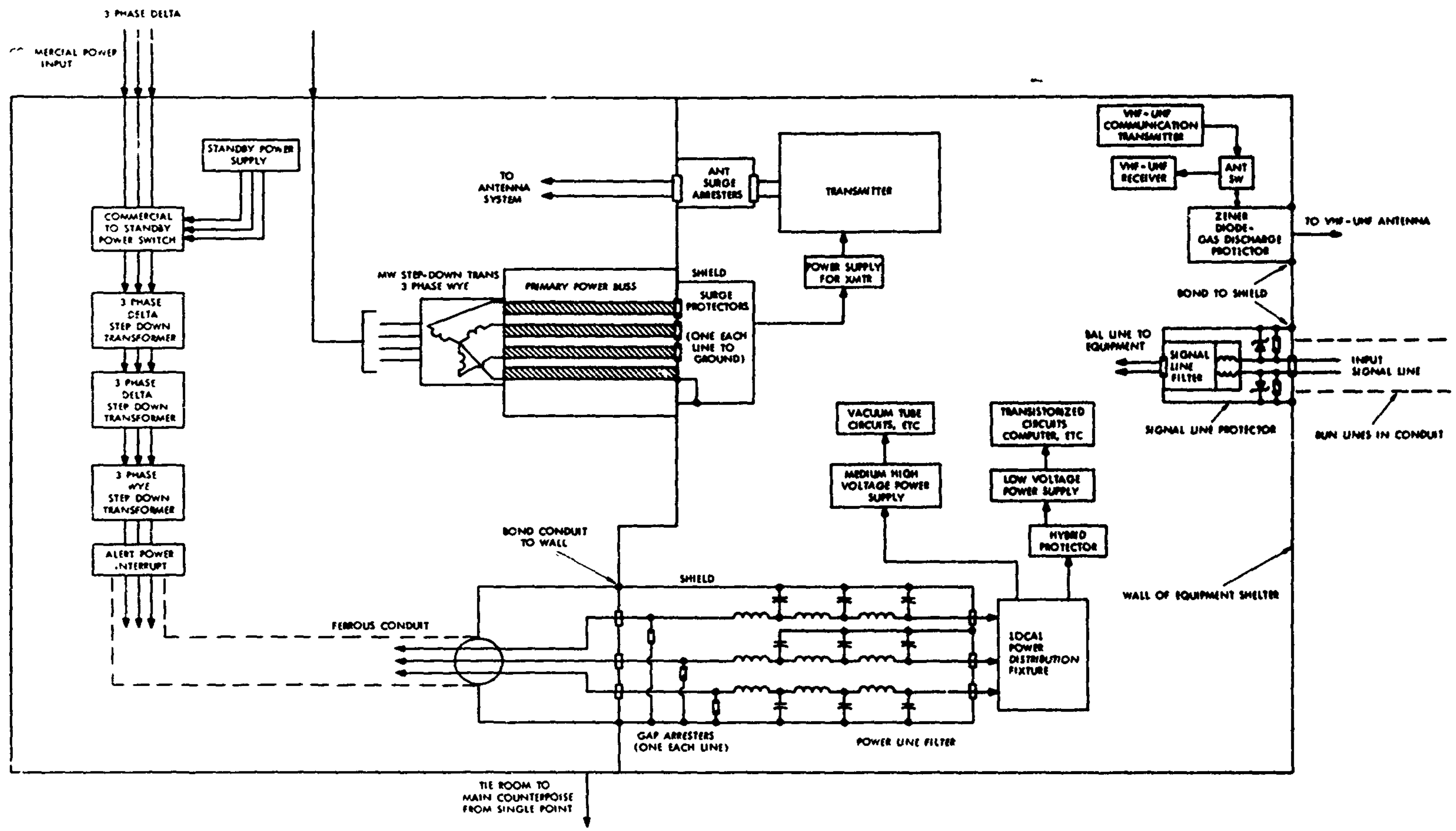


Figure A-16. Power Distribution System illustrating NEMP protection.

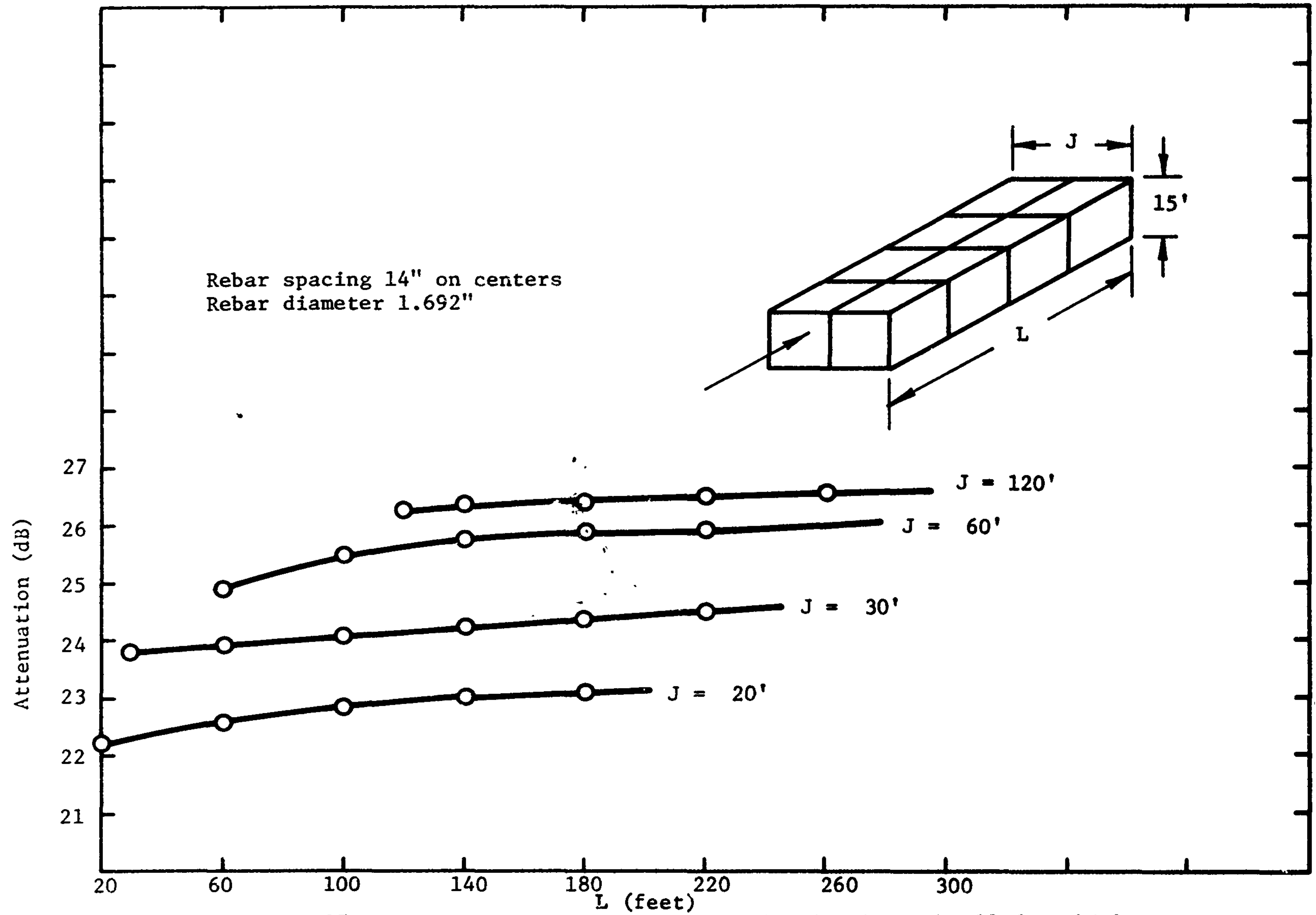


Figure A-17. Center area attenuation of induced voltage by 15 foot high single-course reinforcing steel room.[3]

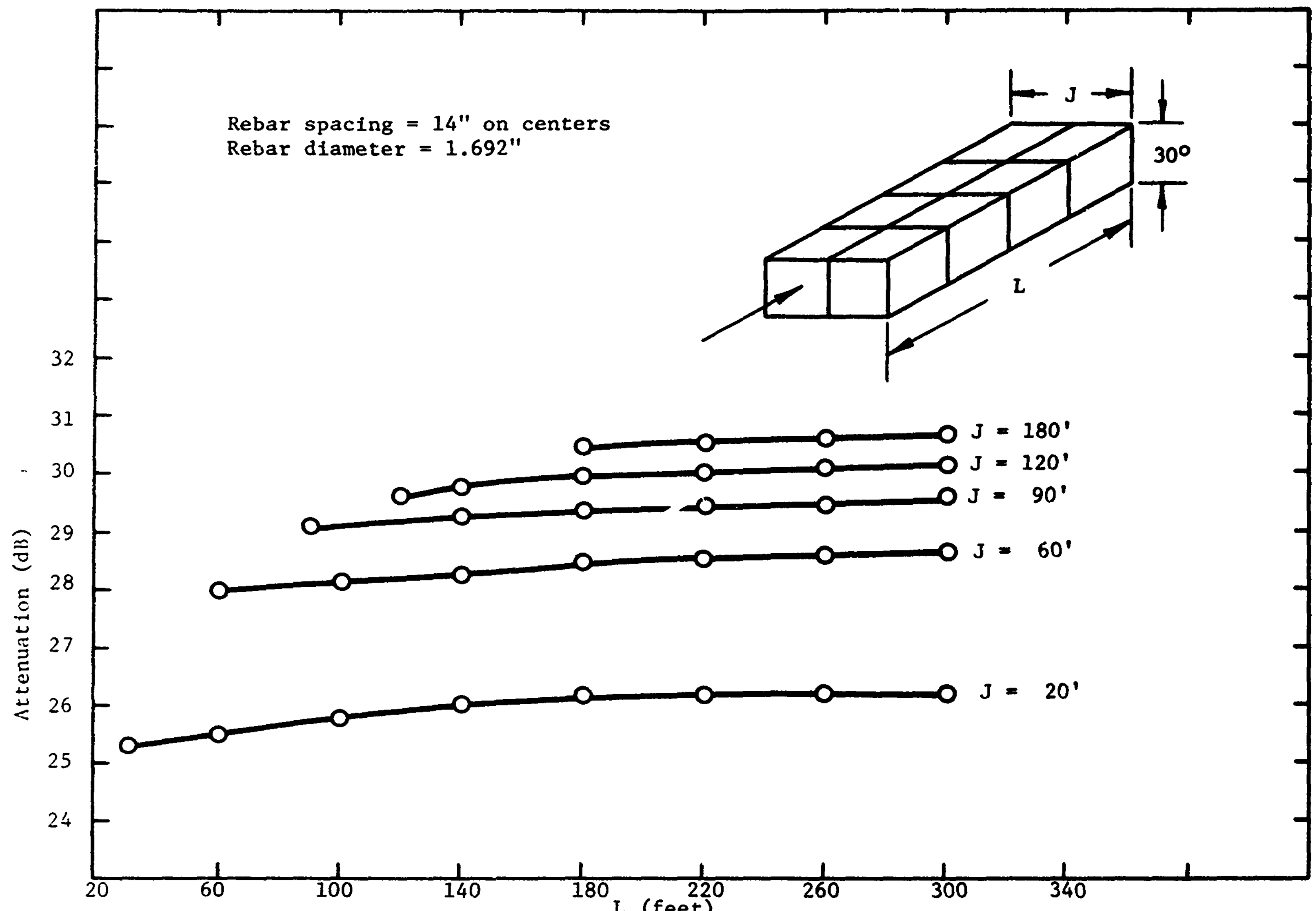


Figure A-18. Center area attenuation of induced voltage by 30 foot high single course reinforcing steel room.[3]

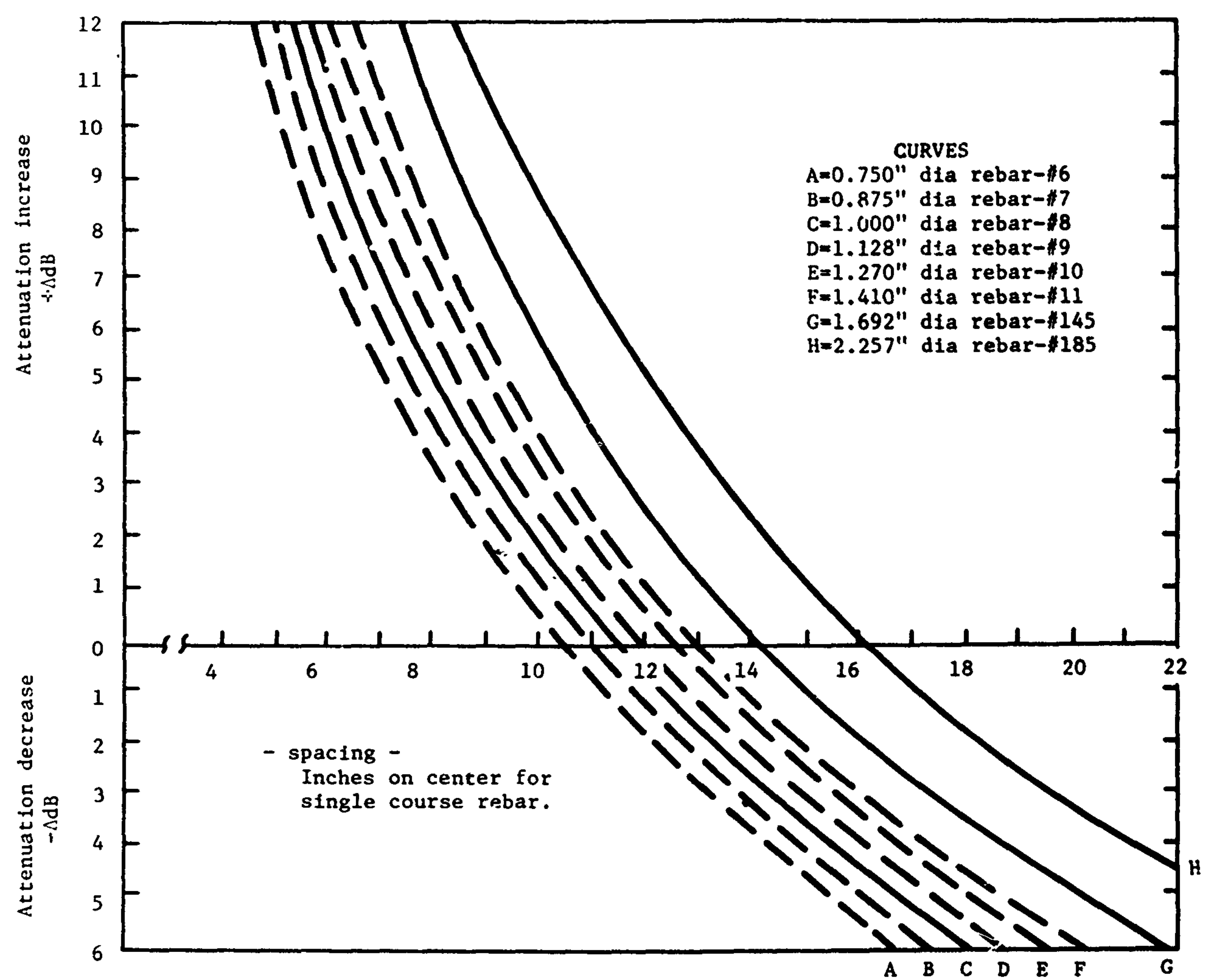


Figure A-19. dB correction curves for various rebar diameters and spacings using single course rebar construction.[3]

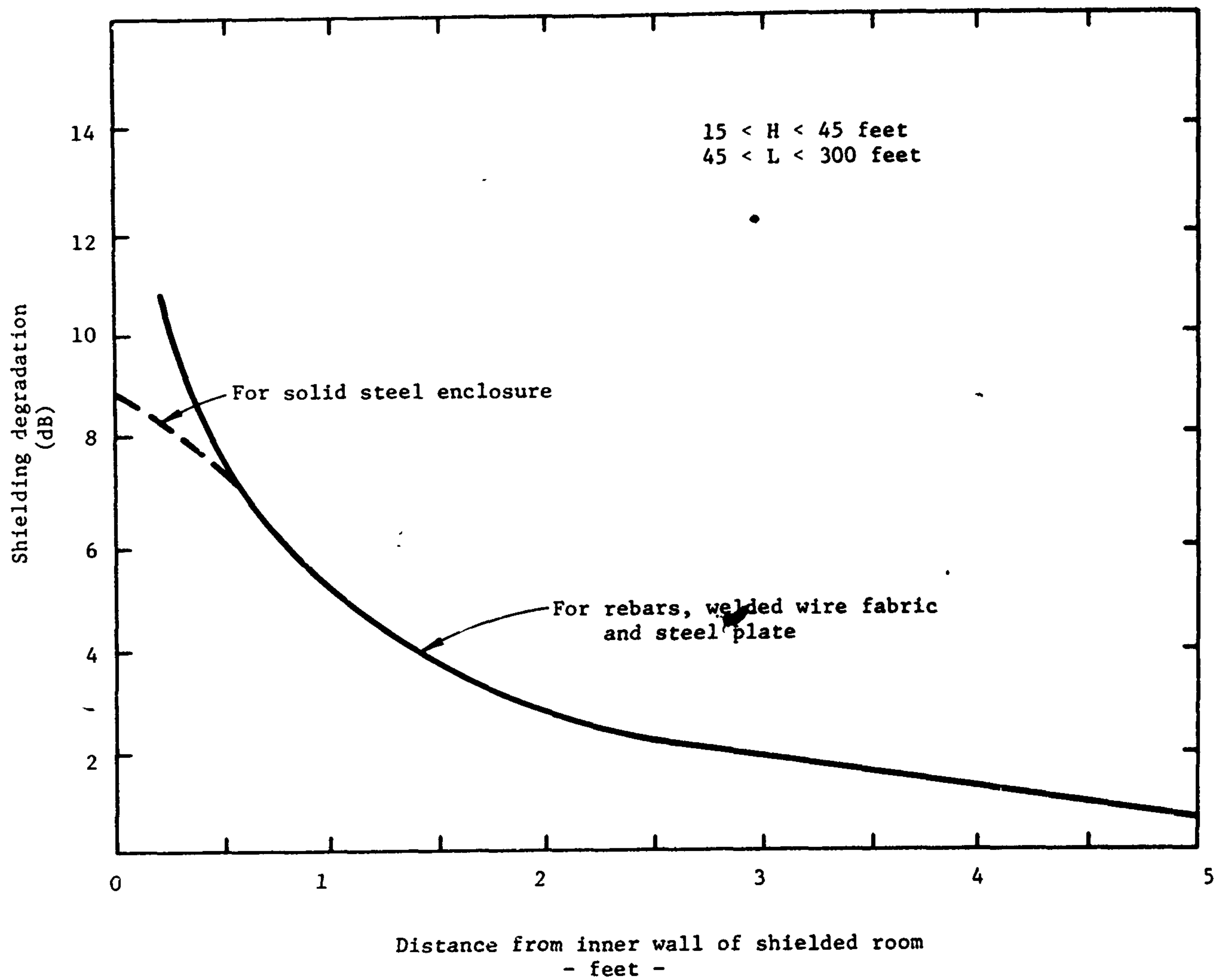


Figure A-20. Shielding degradation vs. distance from wall.[3]

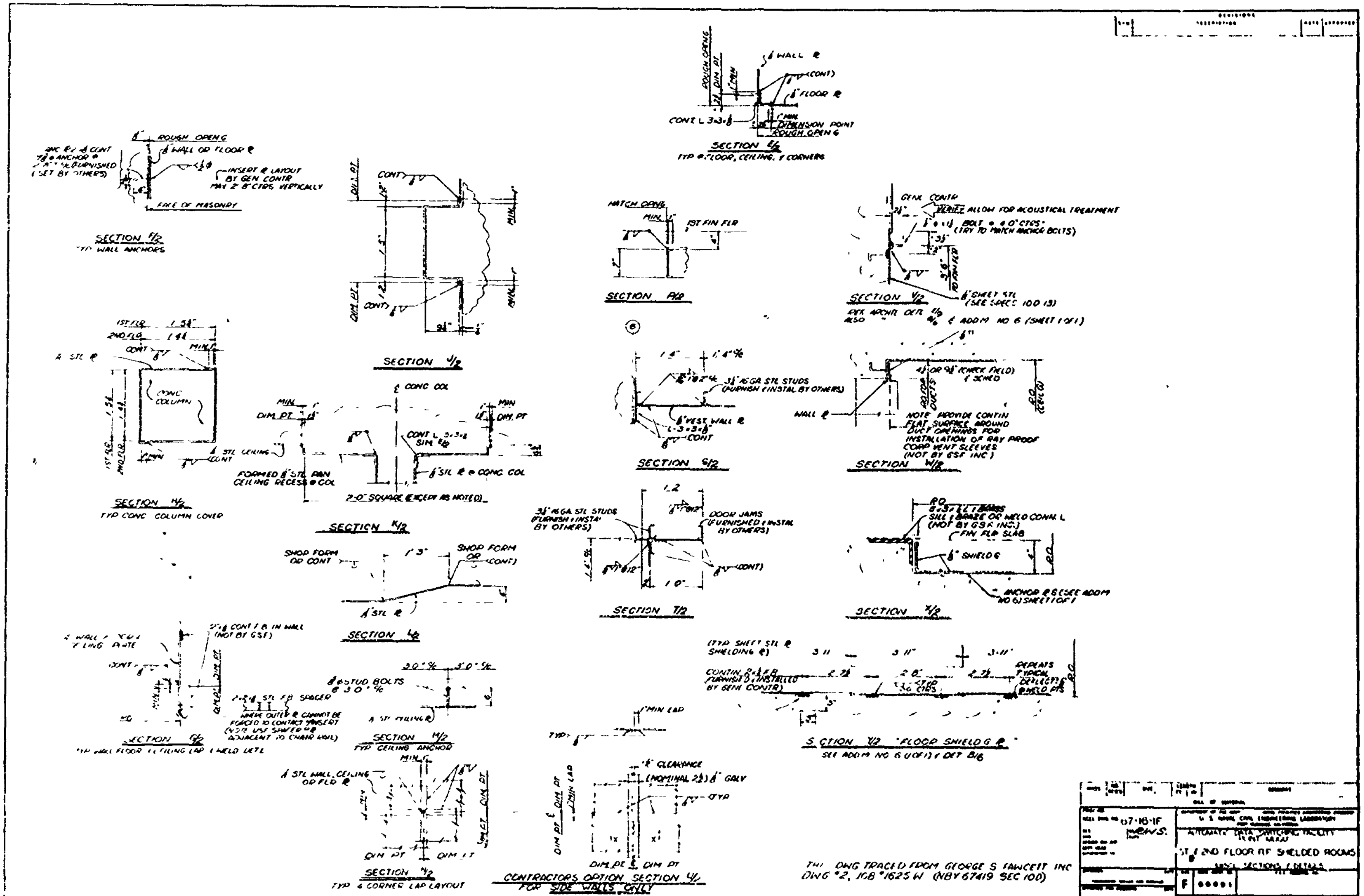


Figure A-21. Construction details of welded liner in reinforced concrete.[19]

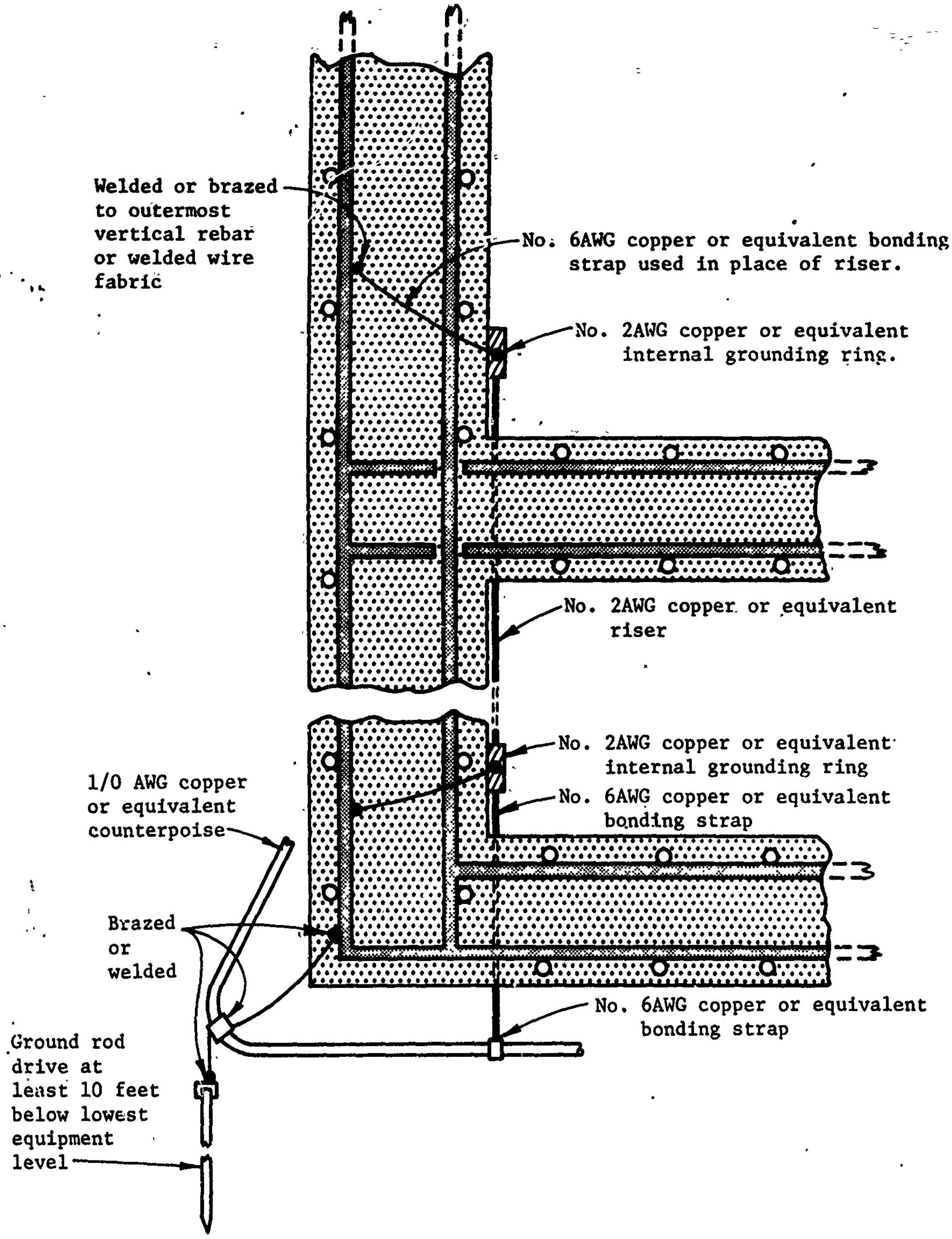


Figure A-22. Internal ground ring counterpoise and ground interconnections.[1/]

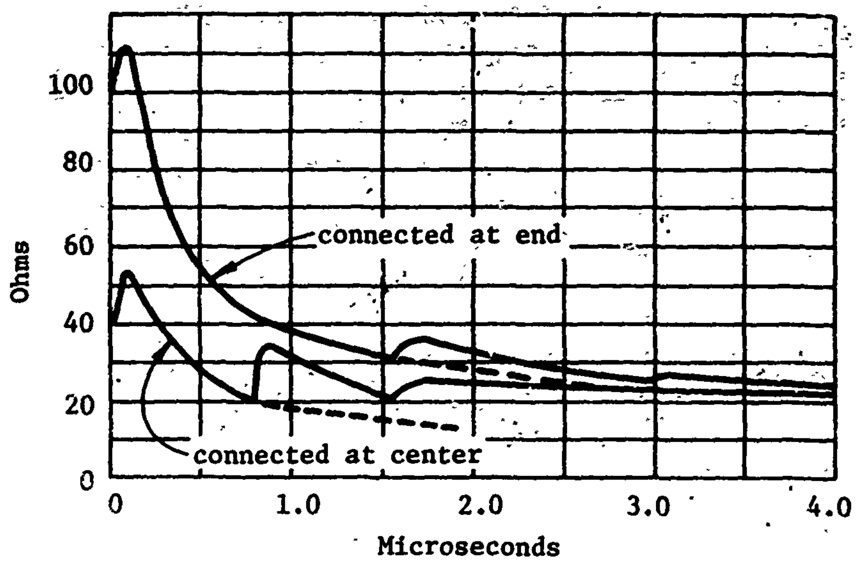


Figure A-23. Surge impedance for unit step current in a conductor with a radius of 0.5 cm, a length of 100 meters and at a depth of 30 cm. Earth restivity 1,000 meter-ohms. Dielectric constant = 10. (from Reference 10).

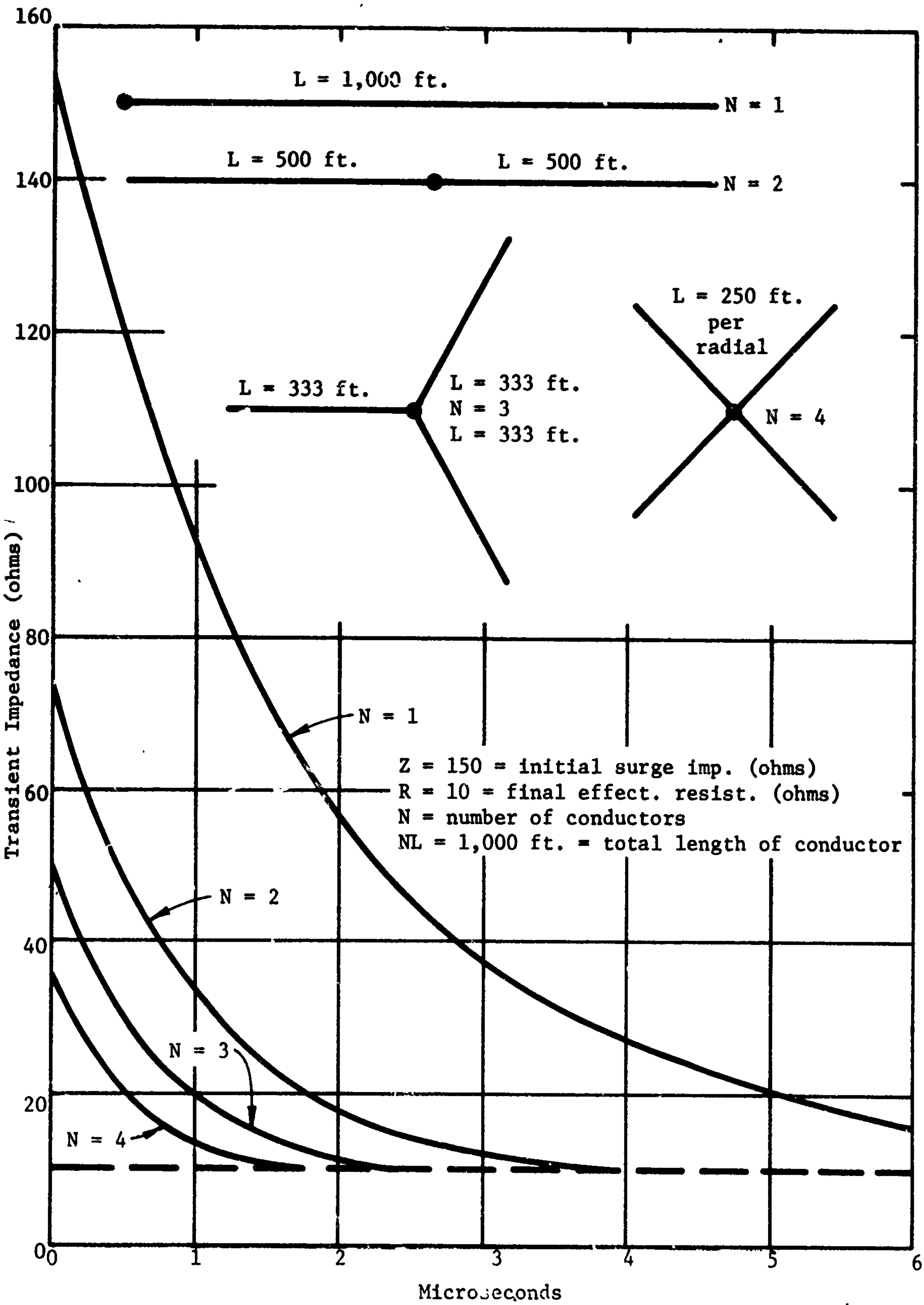


Figure A-24. Effective resistance of counterpoise configurations.[4]

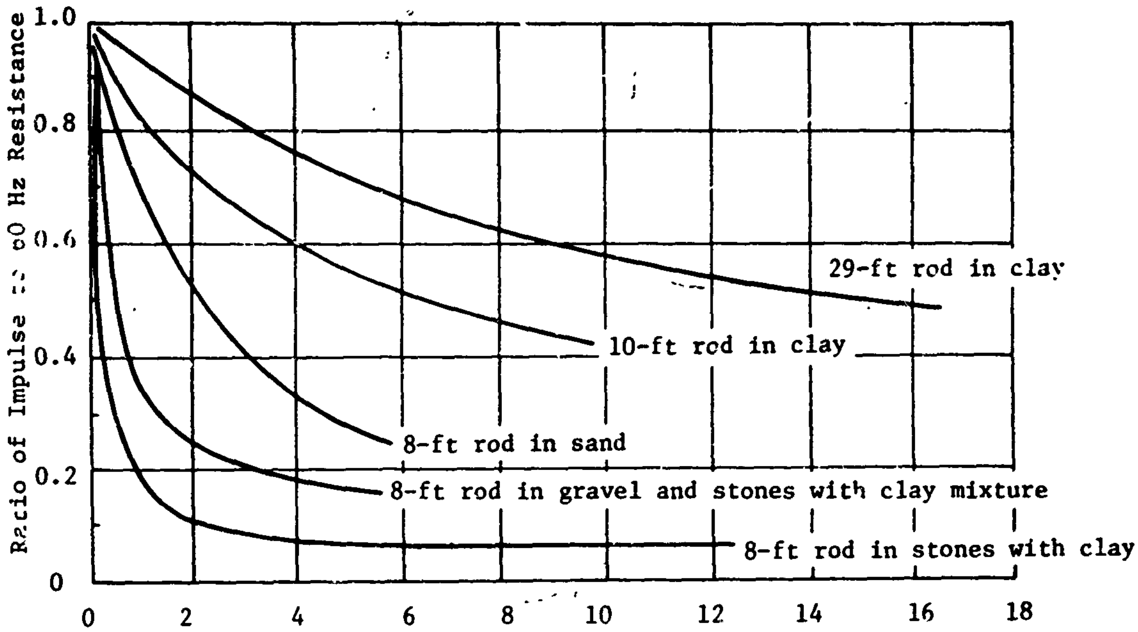


Figure A-25. Soil ionization effects on impulse resistance.[3]

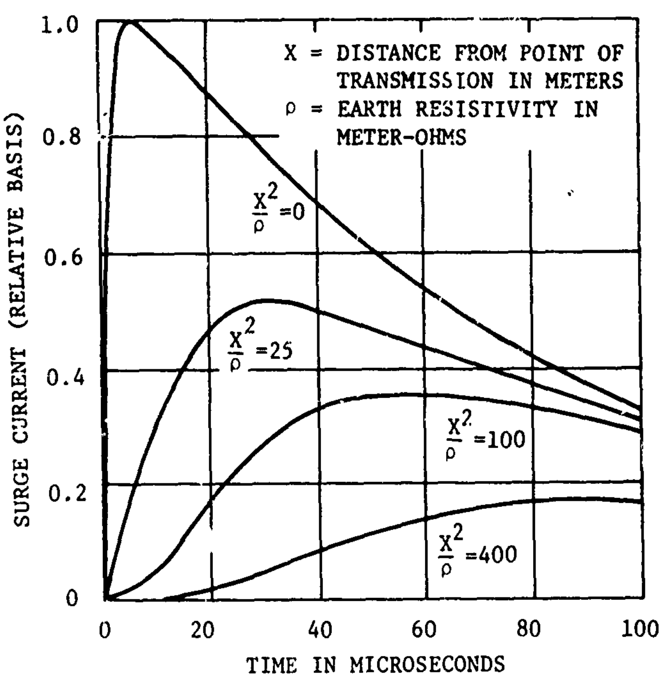
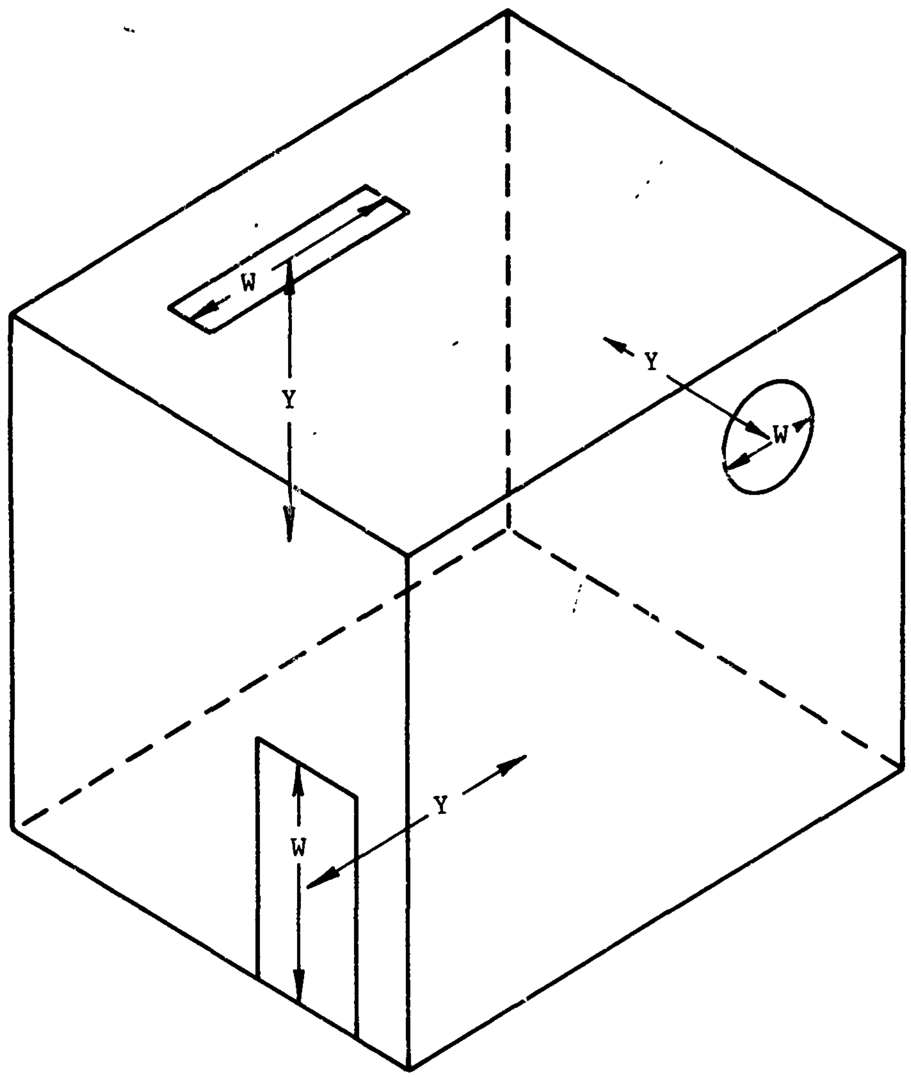


Figure A-26. Attenuation and distribution of surge current in a buried conductor (5x65 μsec initial surge).[4]



W = largest dimension of the opening
Y = distance from the opening

Figure A-27. Typical openings in shielded rooms.[5]

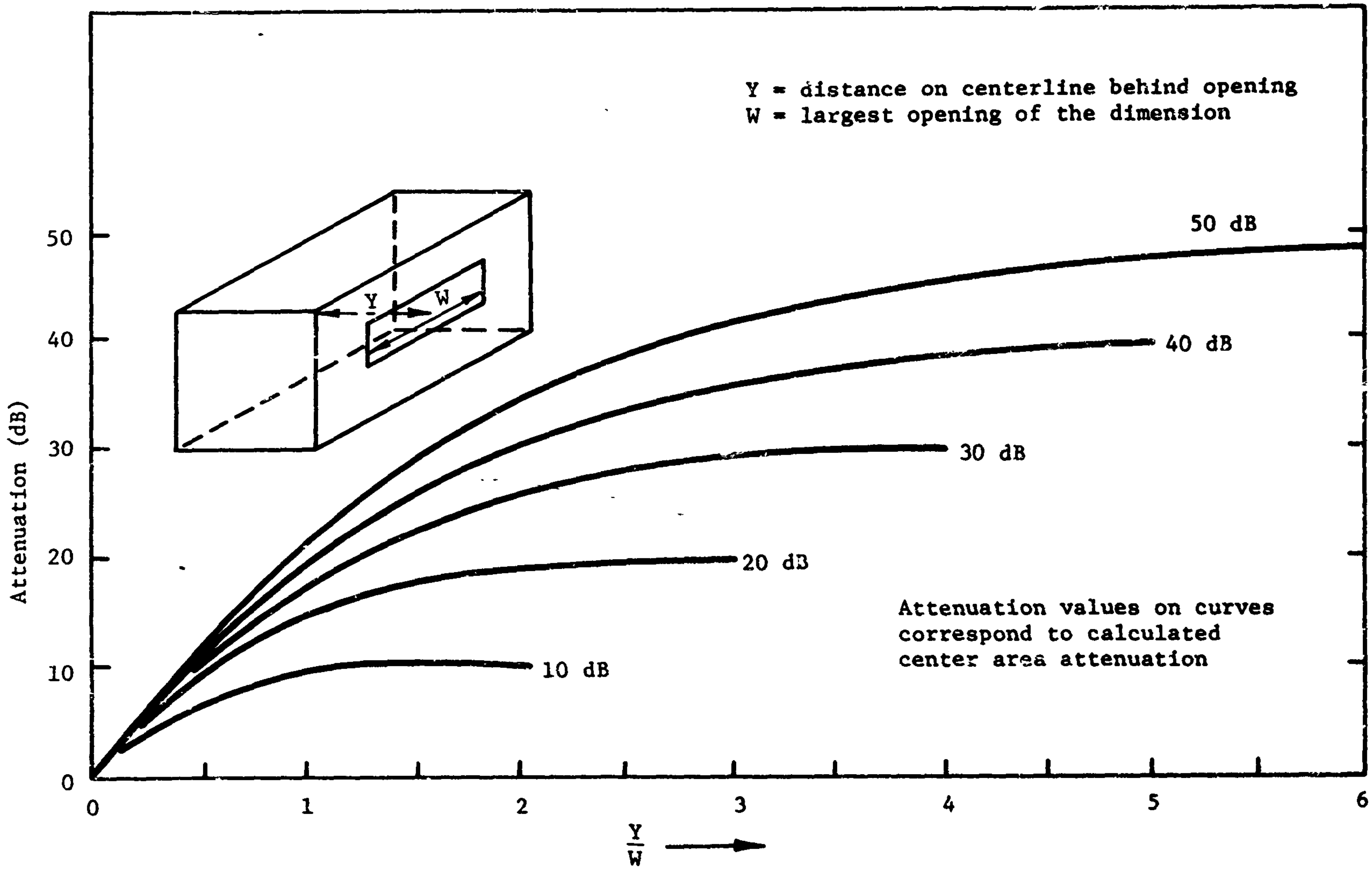


Figure A-28. Opening attenuation of a shielded enclosure as related to the opening dimensions and center area attenuation.[3]

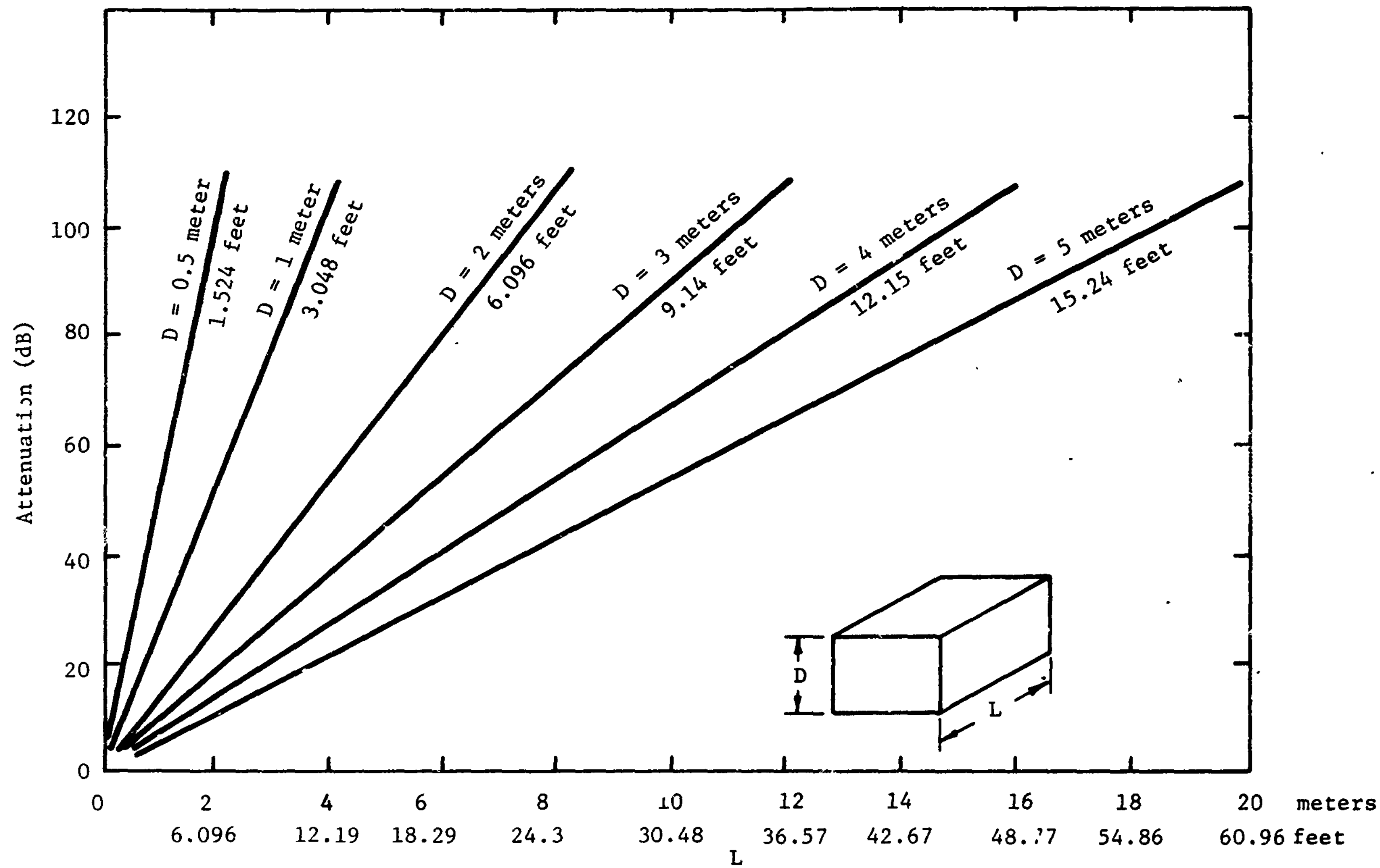


Figure A-29. Wave-guide attenuation as a function of wave-guide dimensions.[5]

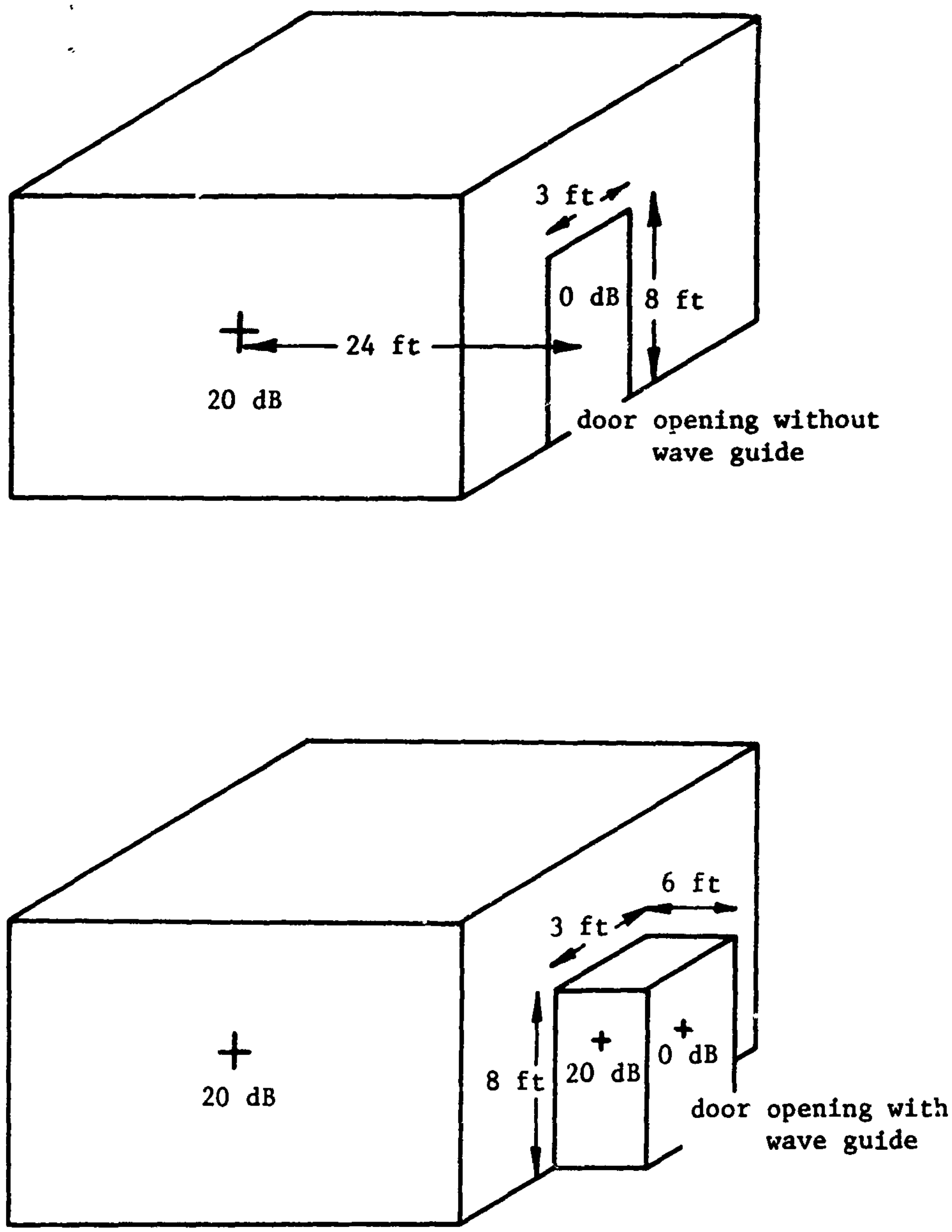


Figure A-30. Application of wave guide attenuation techniques.[5]

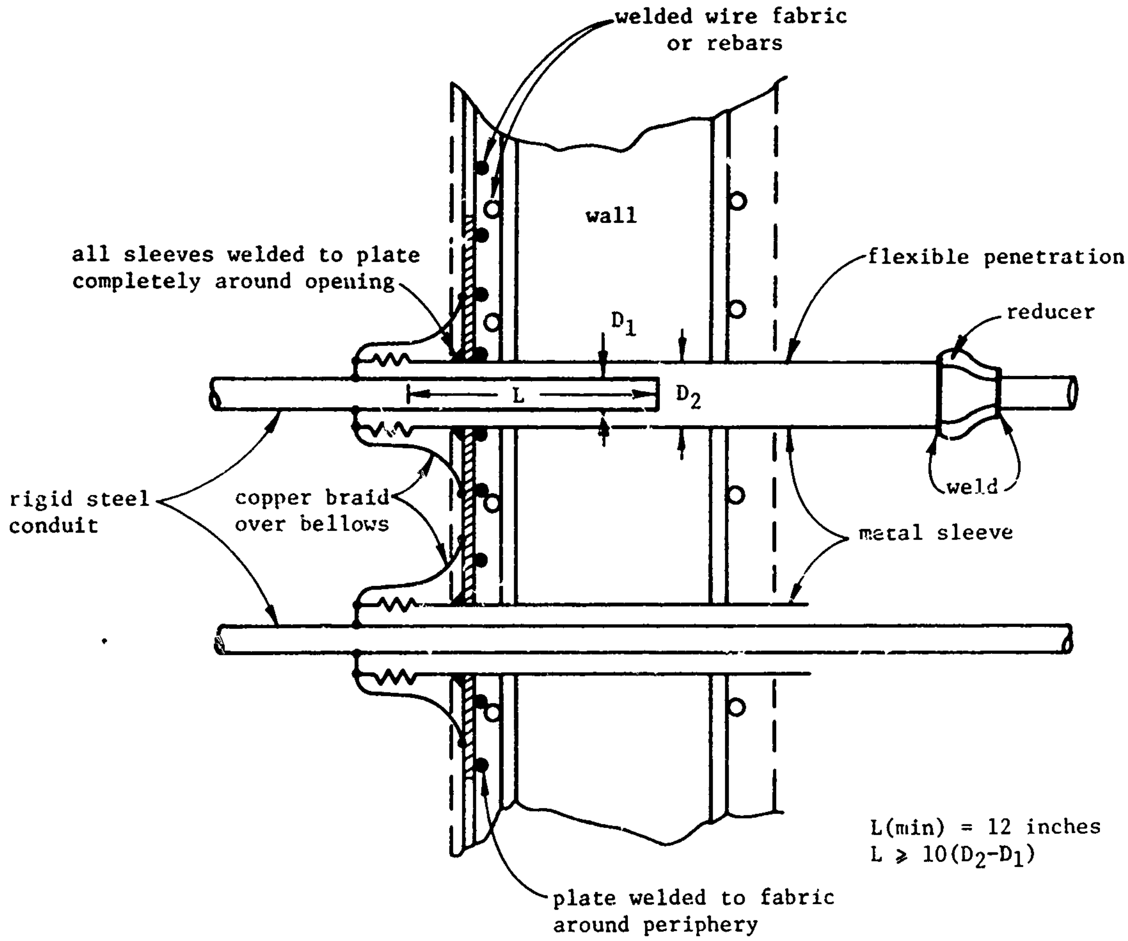


Figure A-31. Penetrations of outside wall with wall shielding.

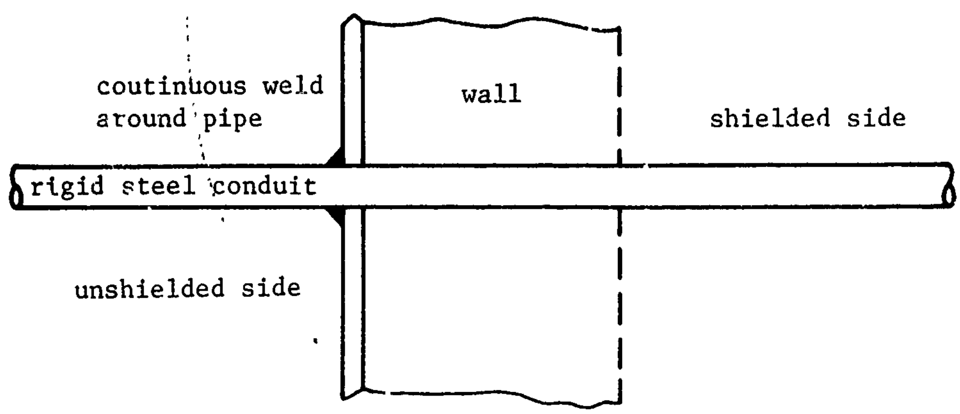


Figure A-32. Wall penetrations with solid-plate shielding.

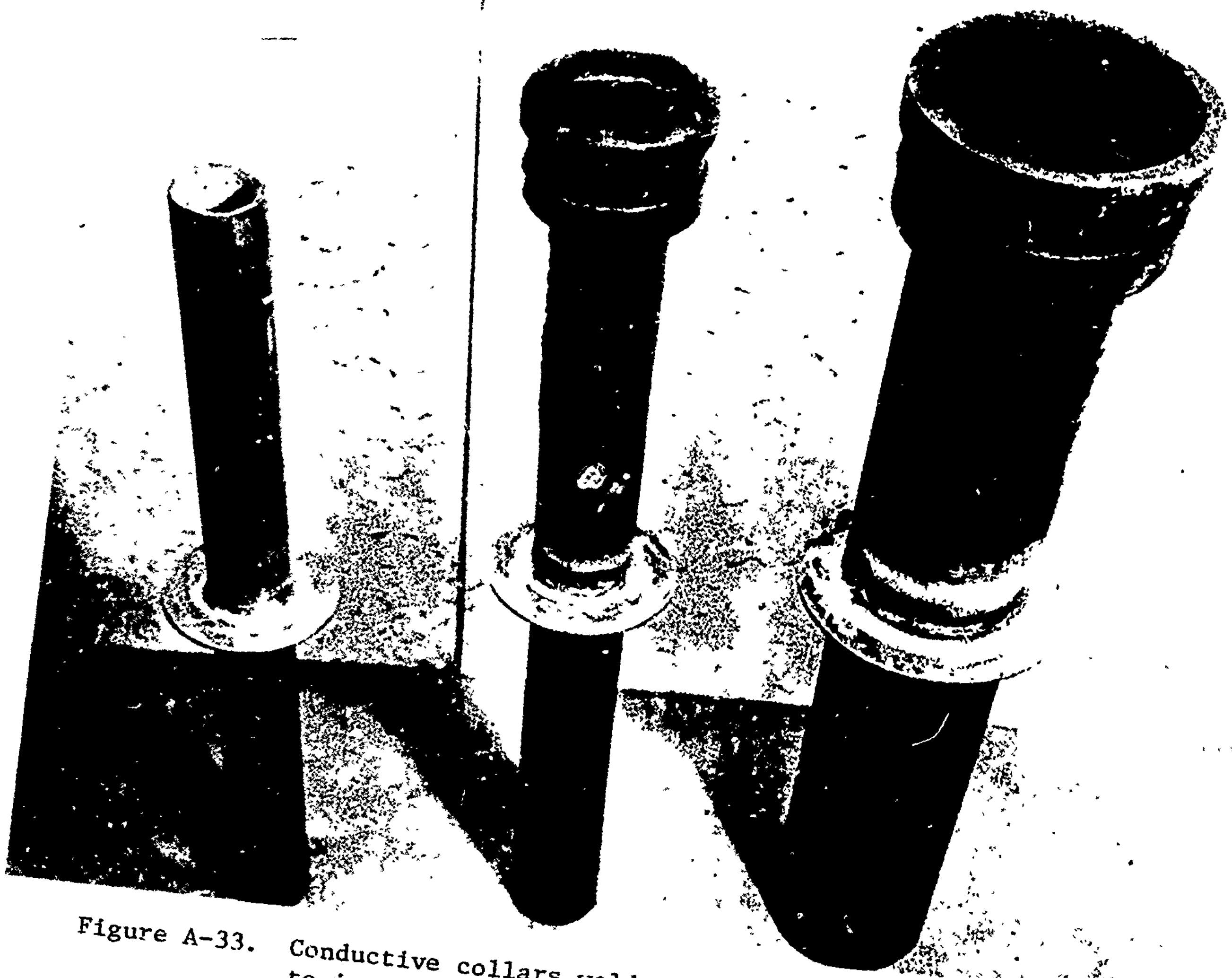


Figure A-33. Conductive collars welded to various penetrations prior to installation.

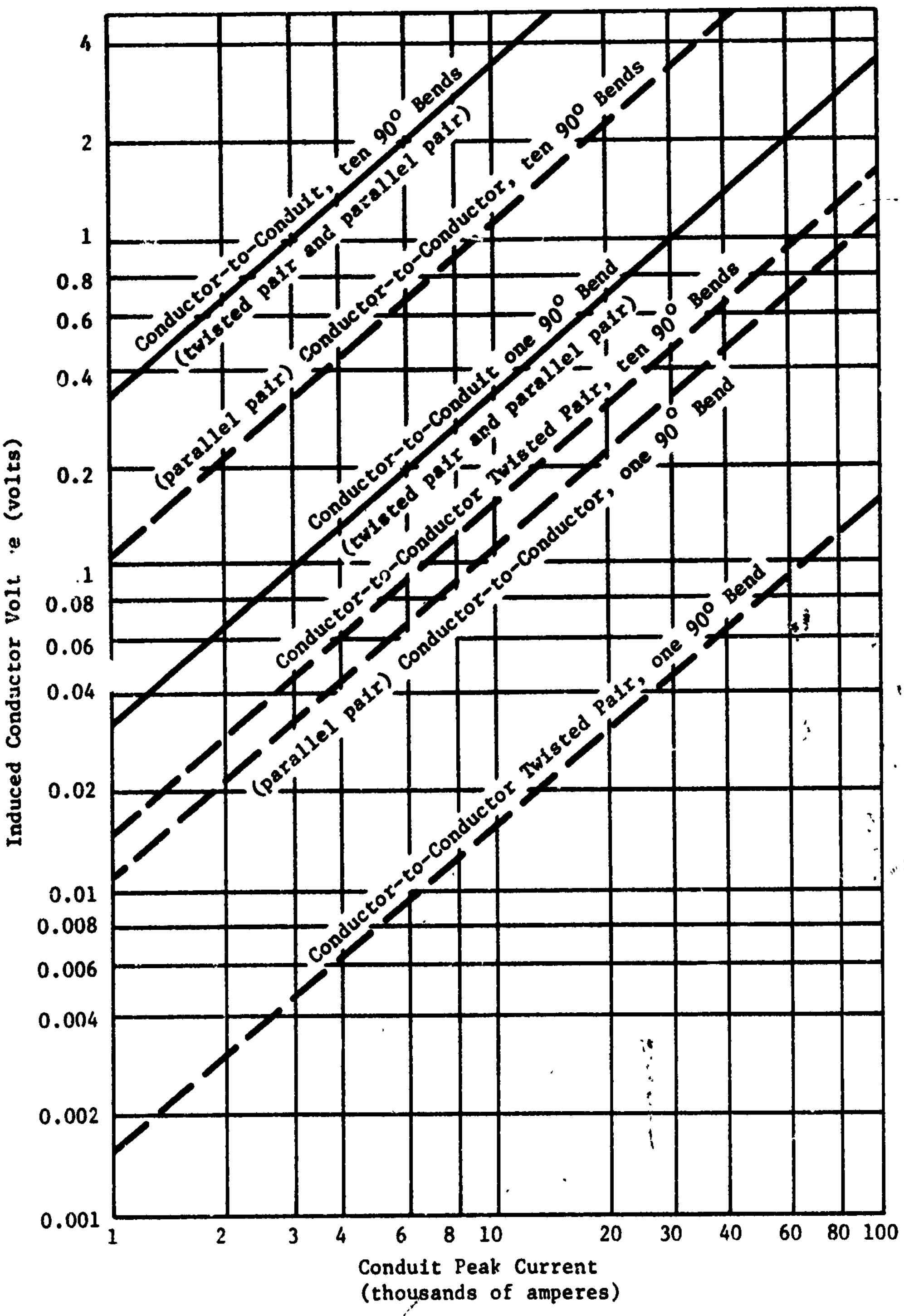


Figure A-34. Induced conductor voltage vs conduit peak current for varying number of bends in standard rigid steel conduit, 2 inch trade size or larger.[17]

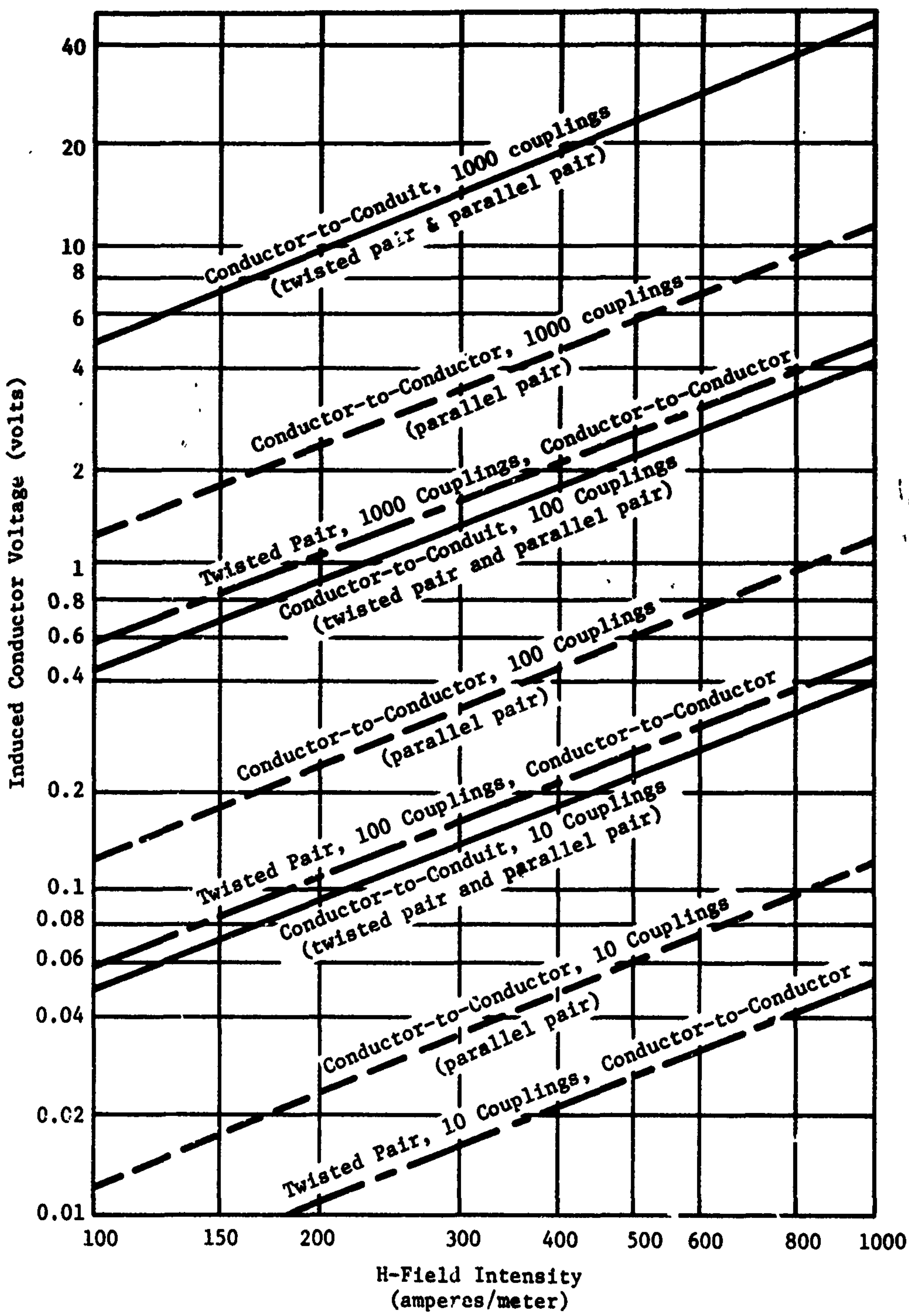


Figure A-35. Conductor voltage vs H-Field intensity for varying number of couplings in standard rigid steel conduit, 2-inch trade size or larger.

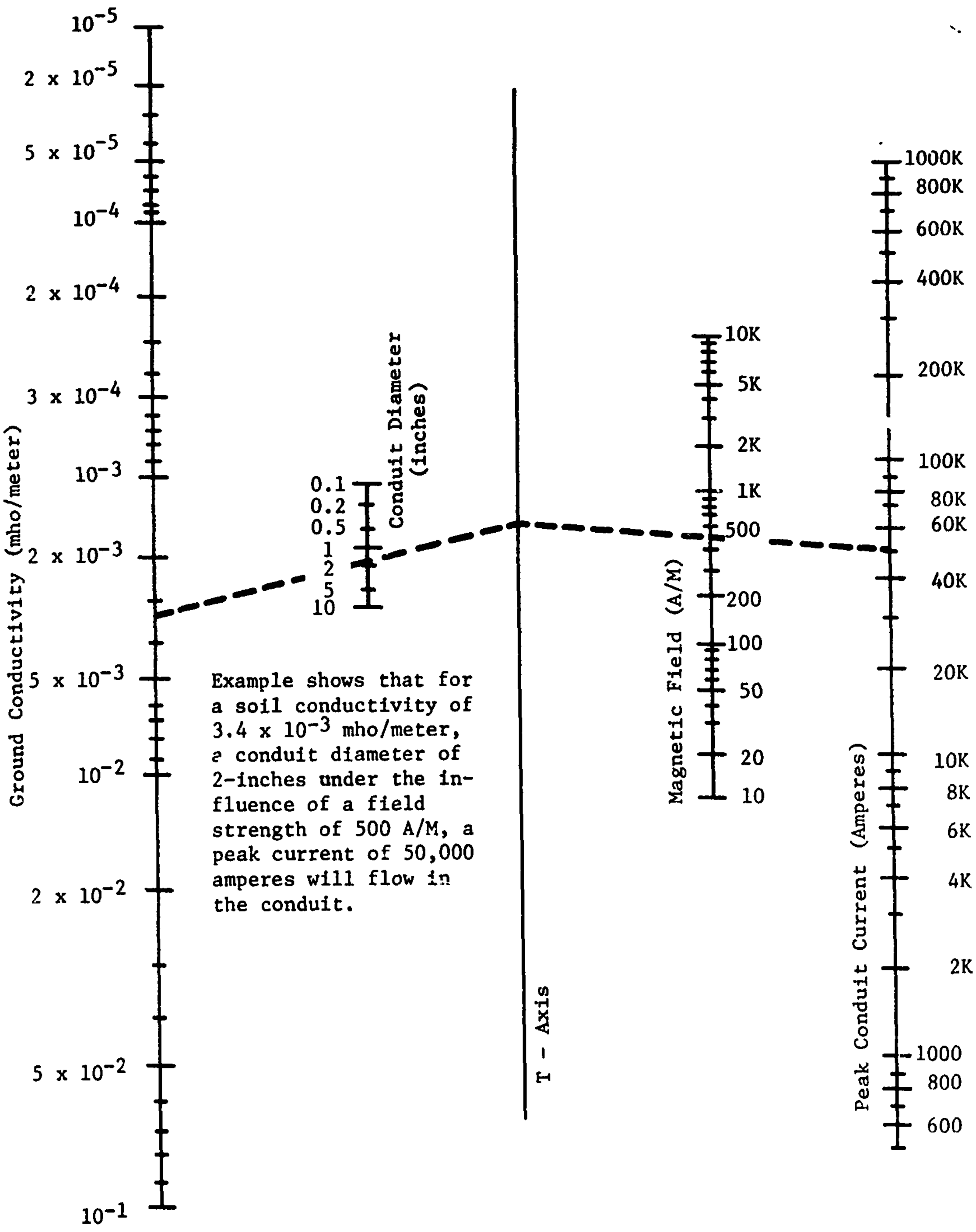


Figure A-36. Nomogram relating peak current, conduit diameter, ground conductivity, and magnetic field.

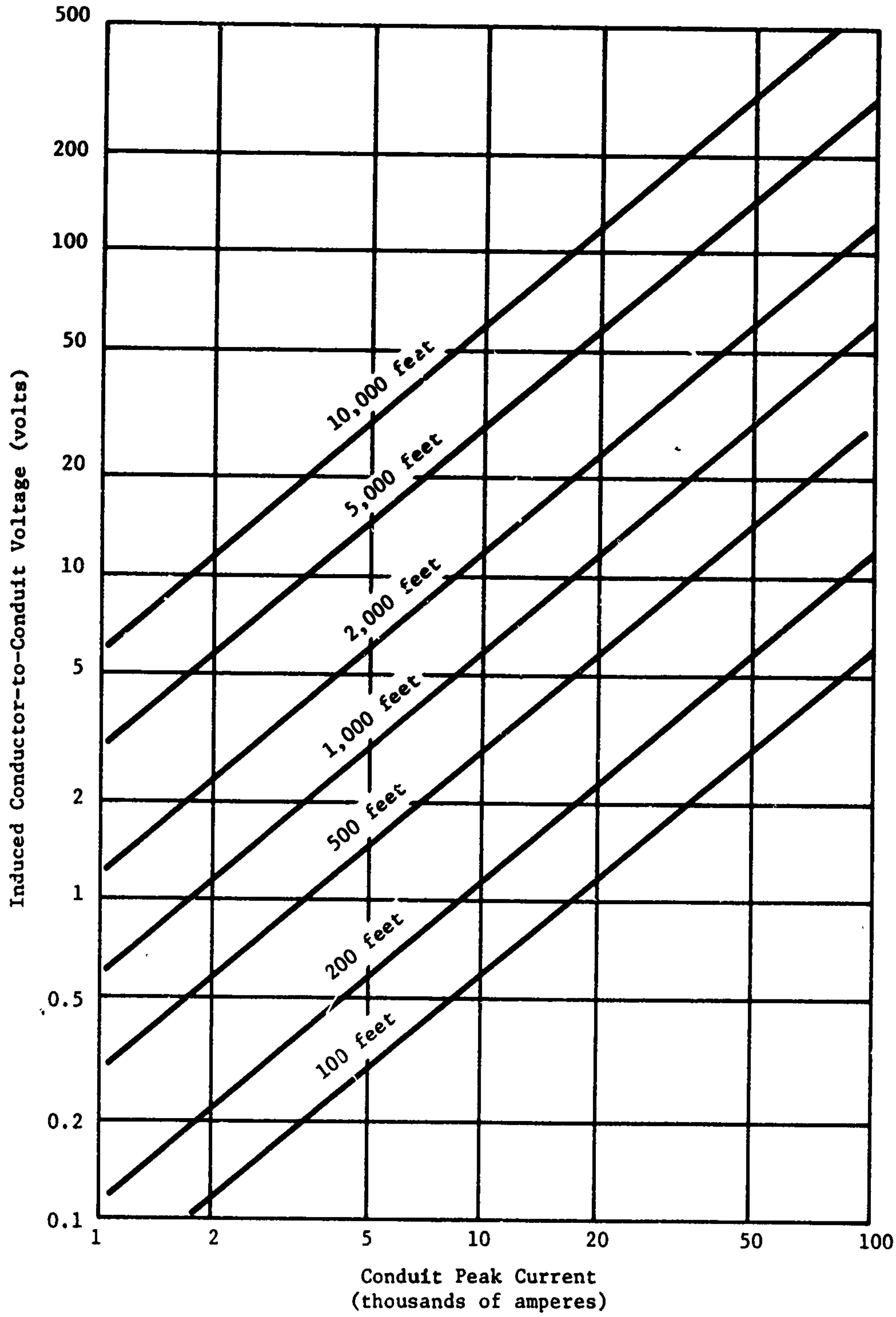
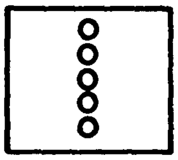
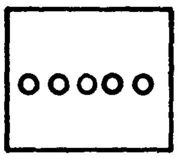


Figure A-37. Conductor voltage vs conduit peak current for varying lengths of standard rigid steel conduit 2-inch trade size or larger with welded joints or threaded couplings.[17]



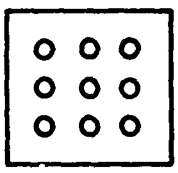
For a vertical conduit arrangement, the induced current on conduits, as determined by the nomograph, Figure A-36, must be multiplied by $1/\sqrt{N_V}$, where N_V is the number of conduits in the trench or duct.

A. Vertical arrangement of conduits in a duct or buried in a trench.



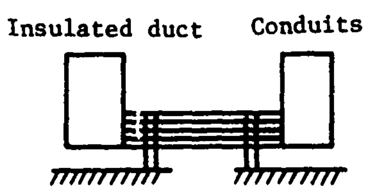
For a horizontal arrangement, the induced current on conduits as determined by the nomograph, Figure A-36, must be multiplied by $1/\sqrt{N_H}$, where N_H is the number of conduits in the trench.

B. Horizontal arrangement of conduits in a duct or buried in a trench.



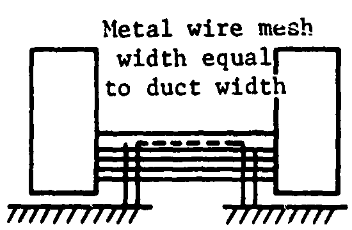
For a vertical and horizontal arrangement, the induced current on conduits, as determined by the nomograph, Figure A-36, must be multiplied by $1/\sqrt{N_V} \times 1/\sqrt{N_H}$, where N_V and N_H are as in A and B above.

C. Vertical and horizontal arrangement of conduits in a duct or buried in a trench.



When conduits are placed in insulated ducts, the induced conduit current, as determined by the nomograph, Figure A-36, must be multiplied by 1/1.25 in addition to the factor given above relating to conduit arrangement.

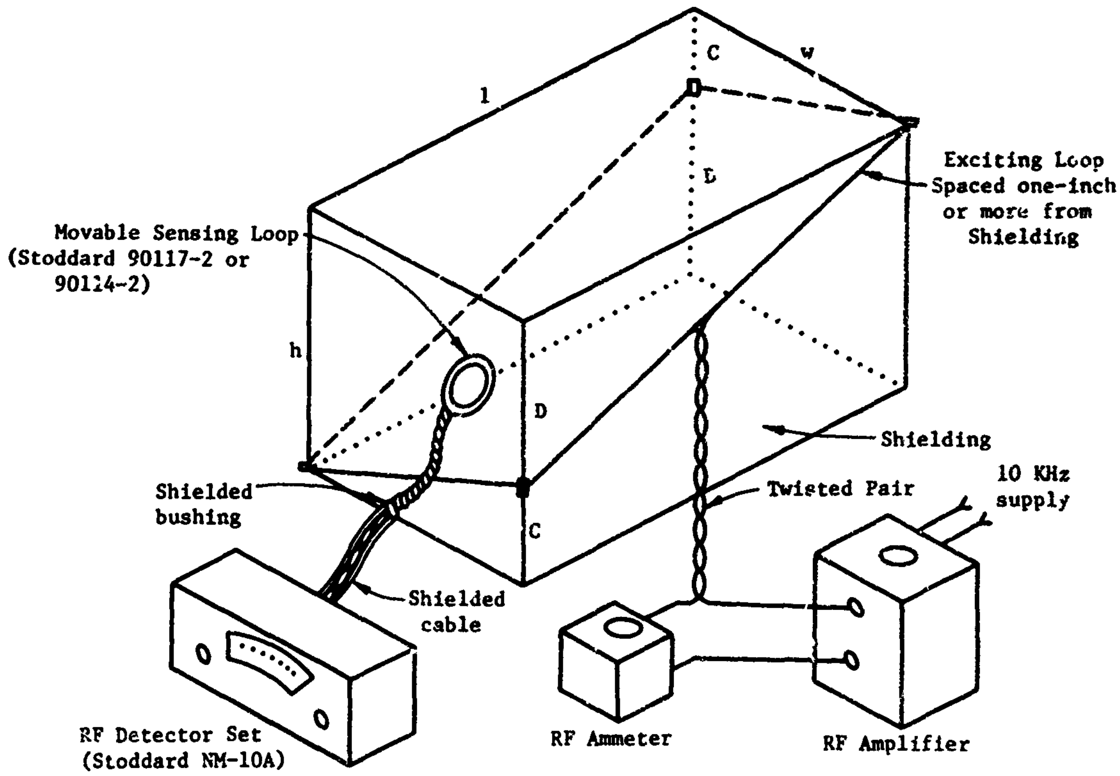
D. Conduits in insulated duct between buildings



When a wire mesh is placed above conduits and connected to the grounding plate at both ends of the duct, the induced current on conduit, as determined by the nomograph, Figure A-36, must be multiplied by the following factors in addition to those given above relating to conduit arrangement. For wire mesh 2.5 feet above conduit multiply by 1/2. For wire mesh 4.0 feet above conduit multiply by 1/3.

E. Conduit ducts with metal wire mesh placed above conduits in duct.

Figure A-38. Physical conduit arrangement affecting the induced current on conduits and the resulting induced voltage on wiring.[17]



$$C = \left(\frac{w}{1 + w}\right) h \qquad C + D = h$$

$$D = \left(\frac{1}{1 + w}\right) h$$

Support exciting loop on standoff insulators. Provide slack in sensing loop cable to permit field evaluations anywhere inside enclosure.

Figure A-39. Test arrangement for evaluation of shielded rooms.[17]

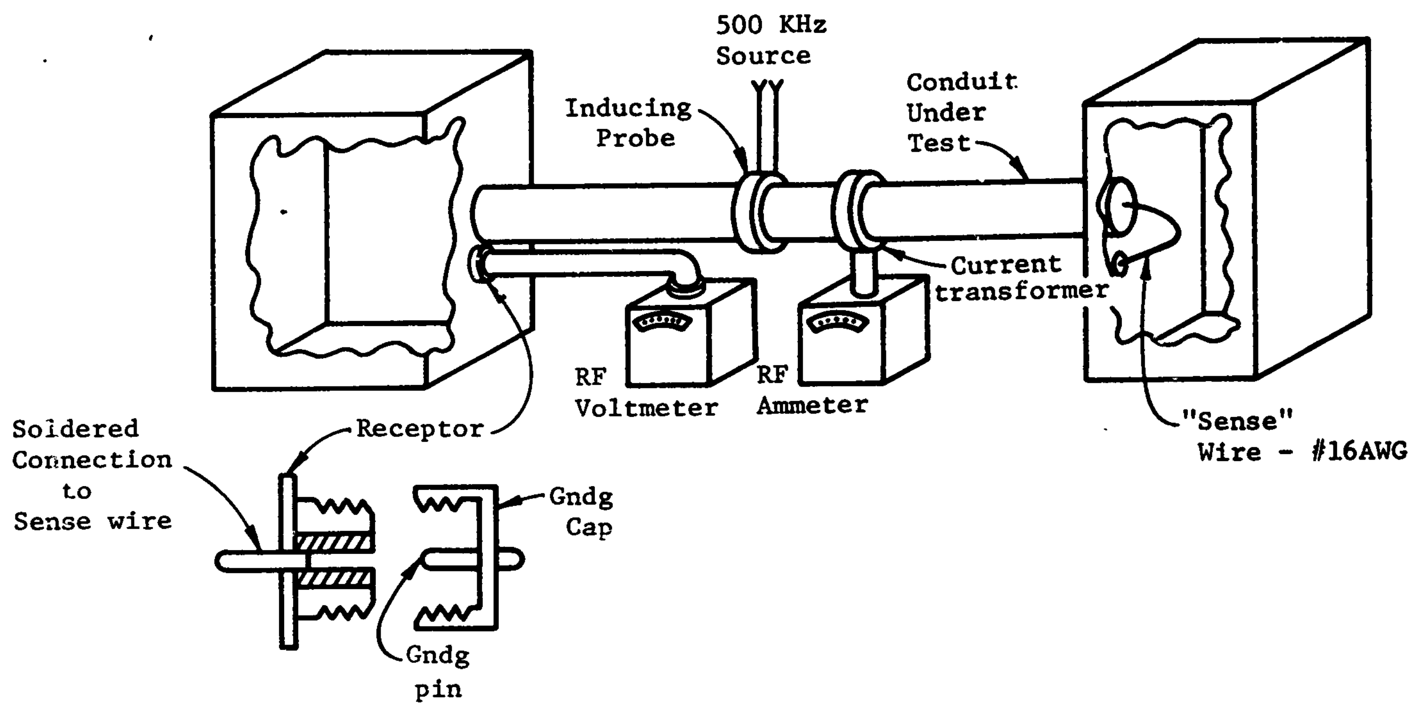
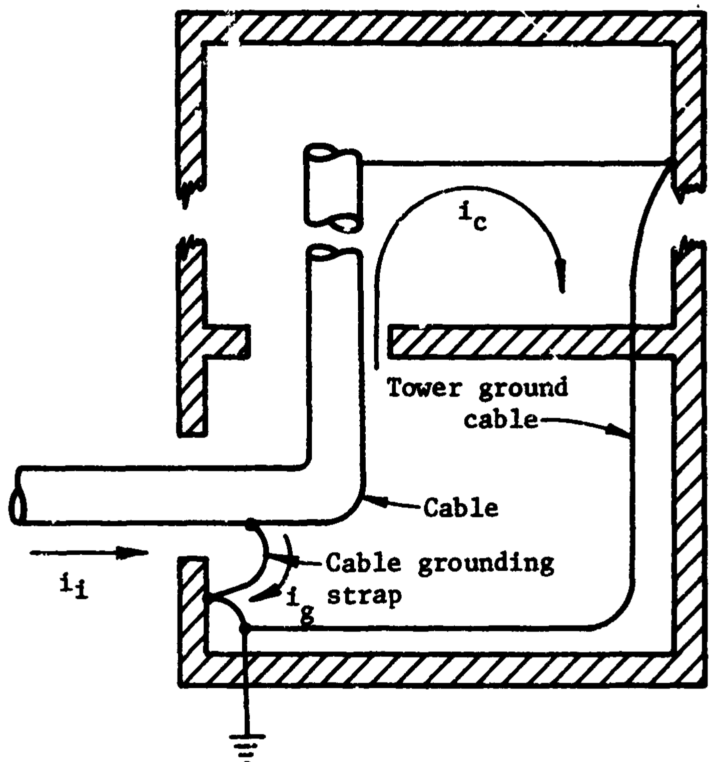
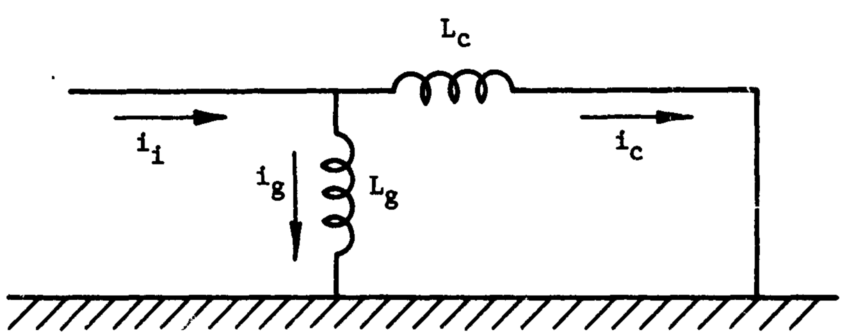


Figure A-40. Arrangements for conduit discontinuity detection testing.[17]

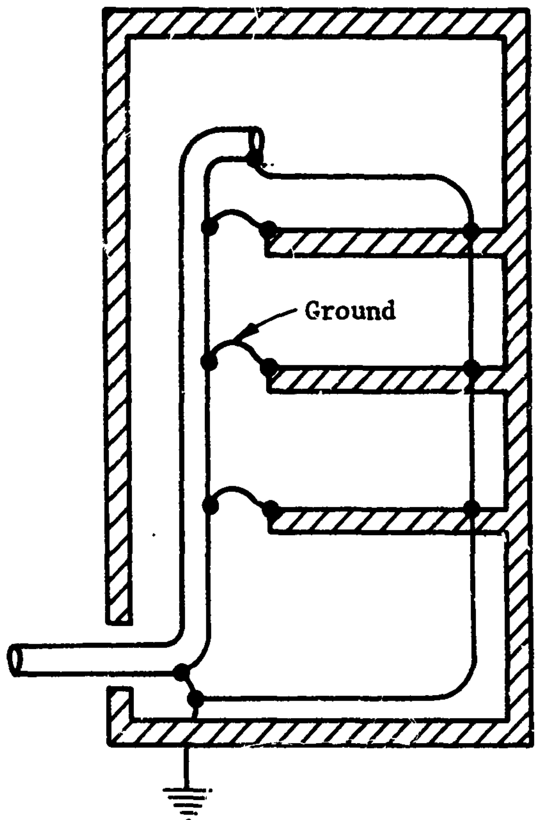


A. Pictorial

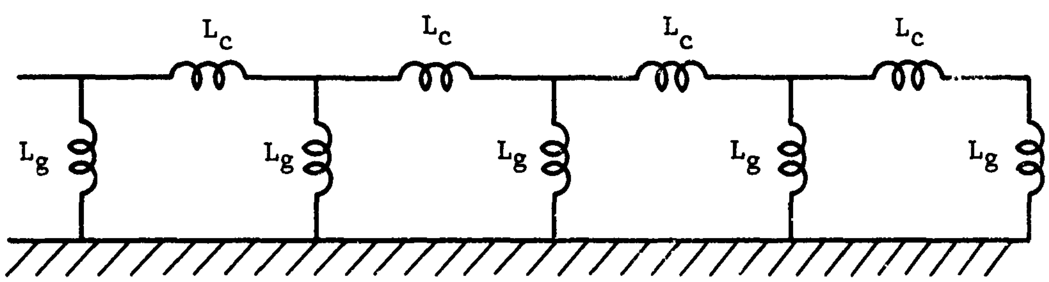


B. Schematic

Figure A-41. Current division on incoming cables.



A. Pictorial



B. Schematic

Figure A-42. Multiple grounding on the cables.

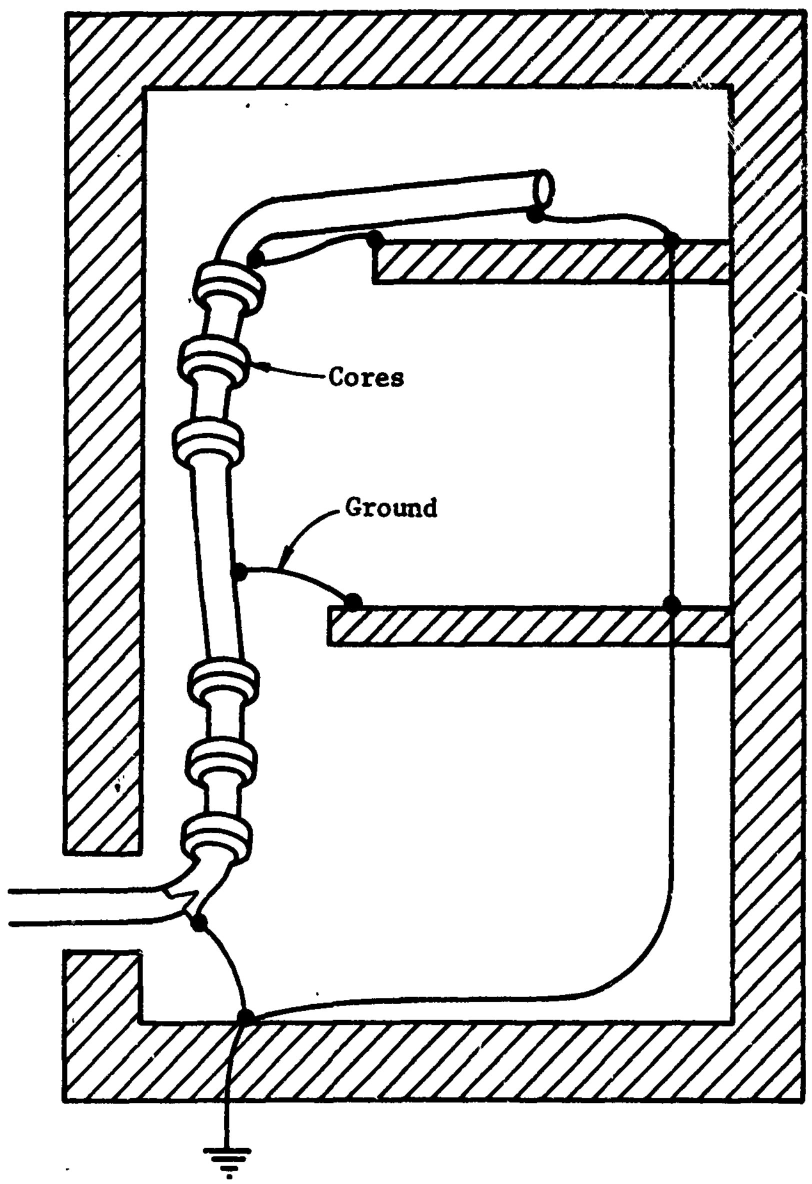


Figure A-43. Magnetic cores tu increase cable inductance.

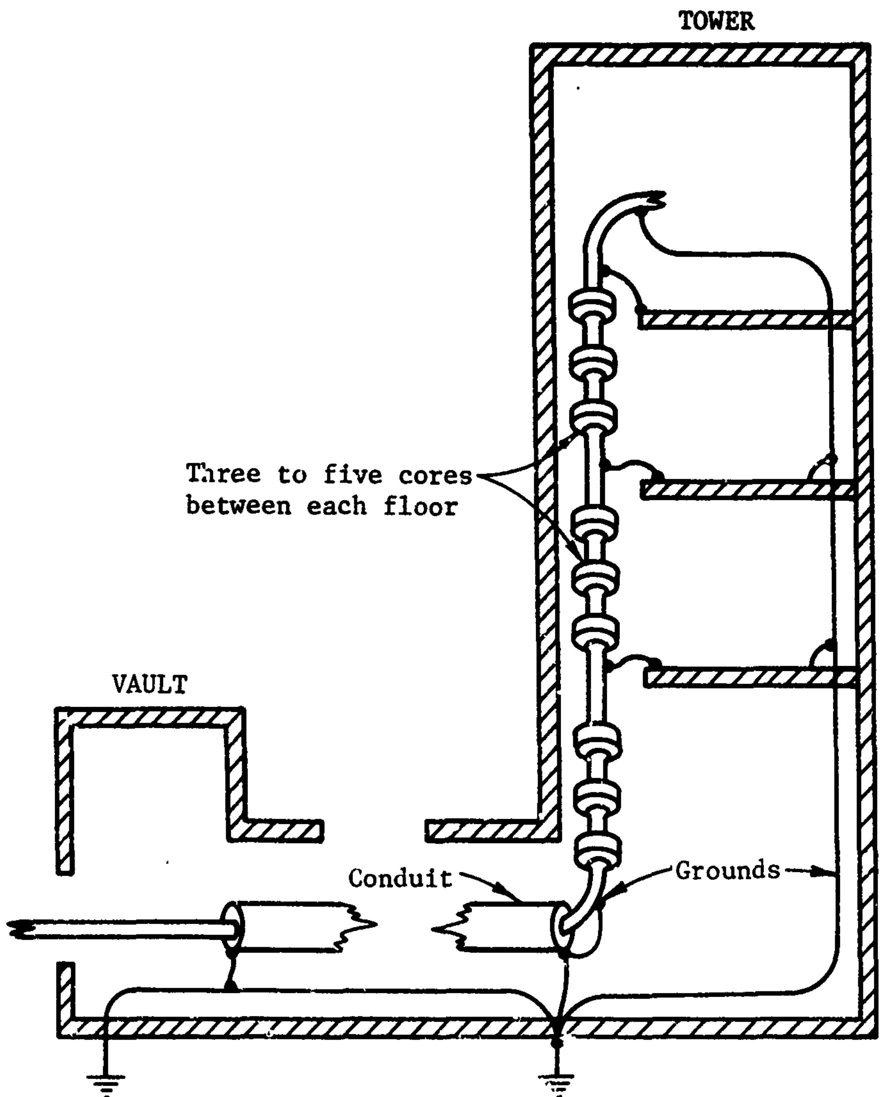


Figure A-44. Communication cable using choke cores and multiple grounds to eliminate shield currents.

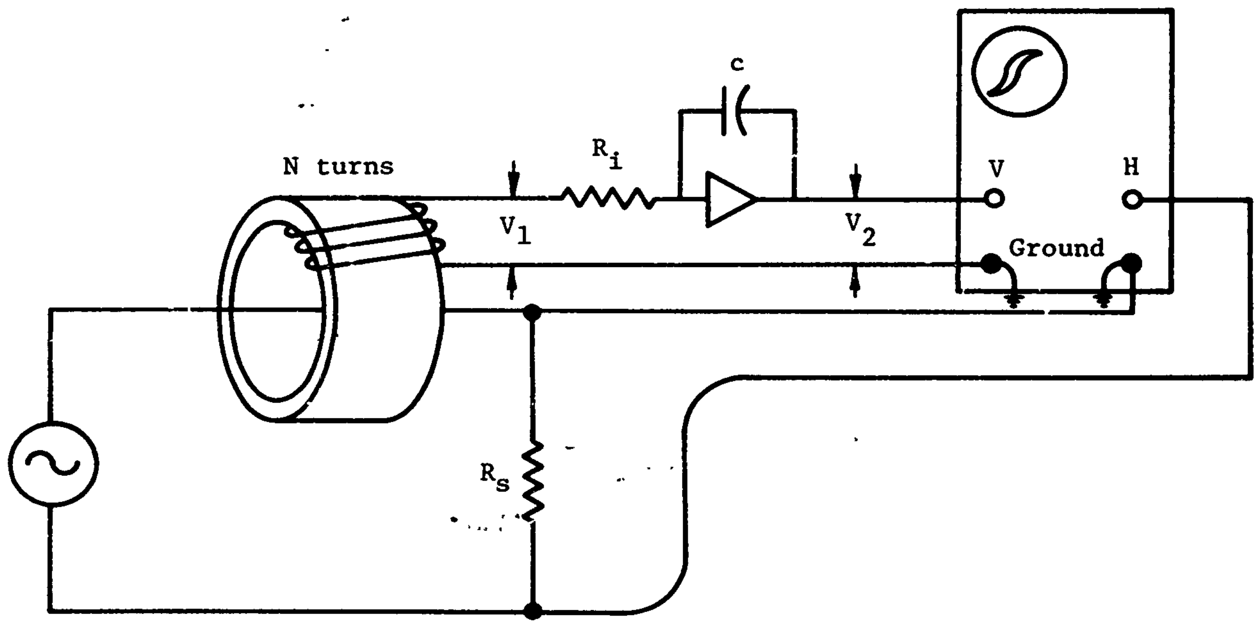
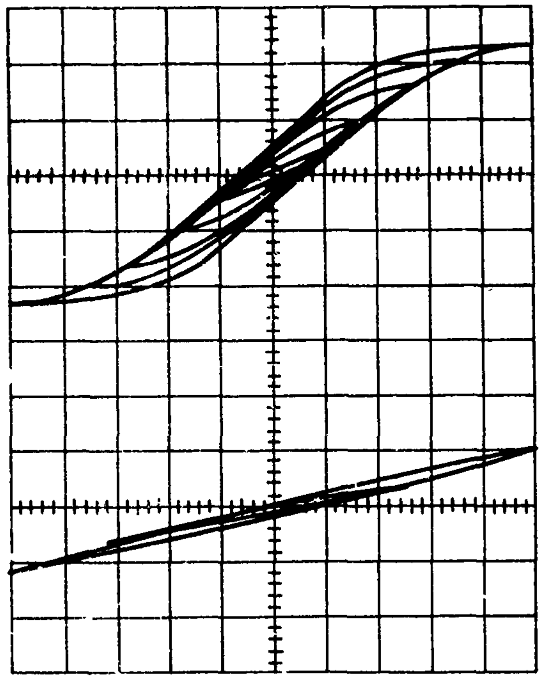


Figure A-45. Determination of magnetic characteristics.



Minimum Air Gap

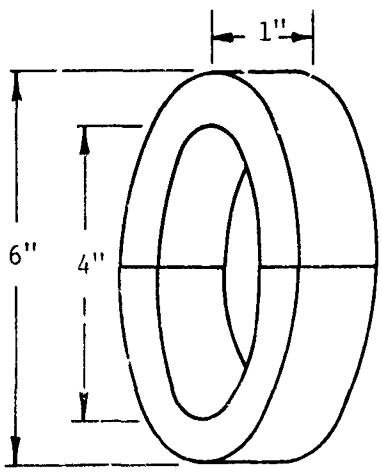
L ≈ 15 µh for one turn

Vertical = 4 x 10^{-4} W/div

Horizontal = 20 At/div

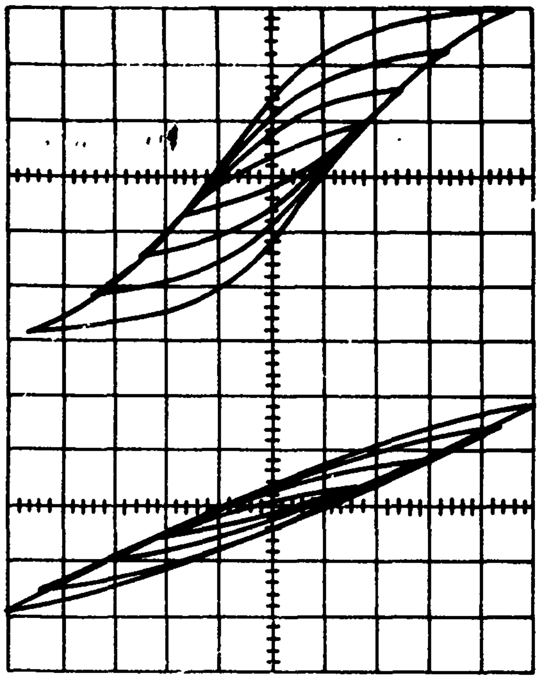
Five Mil Air Gap

L ≈ 5 µh for one turn



Carstedt CRH-84-B, four mil Supersil steel

Figure A-46. Magnetic characteristics of a split toroid.



Minimum Air Gap

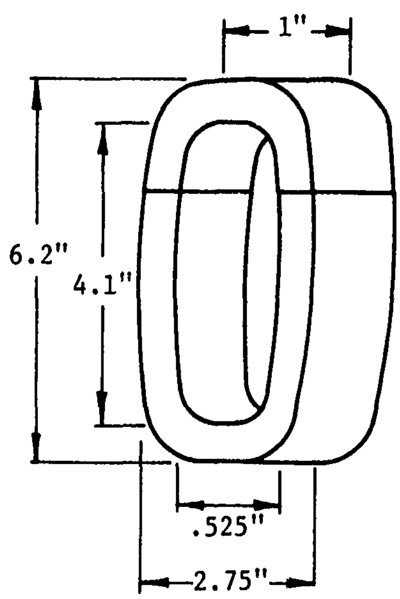
L ≈ 6 μh for one turn

Vertical = 2 x 10^{-4} W/div

Horizontal = 20 At/div

Five Mil Air Gap

L ≈ 3.7 μh for one turn



Three mil steel of unknown manufacture

Figure A-47. Magnetic characteristics of a U core.

REFERENCES

1. Naval Civil Engineering Laboratory. Technical Note N-962: Nuclear Electromagnetic Pulse Effects Design Parameters for Protective Shelters, by H. A. Lasitter, D. B. Clark. Port Hueneme, California. June 1968.

2. Defense Atomic Support Agency. Information and Analysis Center. DASIAC Special Report 41: Electromagnetic Pulse Phenomenology and Effects (U). Santa Barbara, Calif. April 1966. (SECRET RD) (DASA 1731).

3. General Electric Company. Report No. 66005: General NEMP Design Criteria for NIKE-X Power Systems (U), edited by E. R. Uhlig. Pittsfield, Mass. August 1966. (SECRET RD) (Contract DA-49-129-Eng-543).

4. Bell Telephone Laboratories. Technical Report 6 on Contract DA-36-039-SC-73089: Electrical Protection of Tactical Communications System, by J. B. Hays and D. W. Bodle. New York, N. Y. August 1958. (AD224077).

5. General Electric Company. Report No. 67U05: OCE NEMP Program. Development of Criteria for Protection of NIKE-X Power Plant and Facilities Electrical Systems Against Nuclear Electromagnetic Pulse Effects, Status Report, by E. R. Uhlig. Pittsfield, Mass. March 1967. (Contract DA-49-129-Eng-543).

6. Genisco Technology Corporation. Genistron Division. GN 10456: NEMP Handbook for United States Naval Engineering Laboratory, by S. A. Jensen. Los Angeles, Calif. November 1967. (Contract No. N62399-67-C-0024).

7. Naval Civil Engineering Laboratory. Technical Note N-938. Power Filter Insertion Loss Evaluated in Operational Type Circuits, by D. B. Clark, et. al. Port Hueneme, Calif. December 1967.

8. Naval Civil Engineering Laboratory. Technical Report R-444: Lossy Conductors for Attenuation of Power Line Interference, by D. B. Clark. Port Hueneme, Calif. May 1966.

9. Naval Air Development Center. Technical Note NADC-EL-N5507: Problems in Shielding Electrical and Electronic Equipments, by C. S. Vasaka. Johnsville, Pa. June 1955.

10. E. D. Sunde. Earth Conduction Effects in Transmission Systems. New York. Van Nostrand. 1949.

11. Naval Civil Engineering Laboratory. Technical Report R-454: Construction and Evaluation of a Prototype Electromagnetically Shielded Room, by H. A. Lasitter. Port Hueneme, Calif. June 1966.

12. W. Jarva. "Shielding Efficiency Calculation Methods for Screening, Waveguide Ventilation Panels, and other Perforated Electromagnetic Shields," in Proceedings, Seventh Conference on Radio Interference Reduction and Electronic Compatibility. November 7-9, 1961. Chicago, Illinois. Chicago, Ill., Armour Research Foundation, 1961. pp. 478-498.

13. H. B. Dwight Calculation of Resistances to Ground, Electrical Engineering Volume 55. December 1936.

14. Shielding Effectiveness Test Report of Telecommunications Switching Facility Building 127, San Nicolas Island. Contract NBY-67344. TR6661 8 Oct 1966.

15. Electromagnetic Shielding Effectiveness Test Report on Automatic Data Switching Facility, Pt. Mugu, Calif. Prepared for Cardau Construction Company by Cornell-Dubillier Electronics, Venice, Calif. May 1967.

16. General Electric Company. Report No. 67U11: OCE NEMP Program. Development of Criteria for Protection of NIKE-X Power Plant and Facilities. Electrical Systems Against Nuclear Electromagnetic Pulse Effects, by E. R. Uhlig. Pittsfield, Mass. 1 Dec 1967. (Contract DA-49-129-Eng-543).

17. Conductor Voltages Caused by Pulse Currents Flowing in a Steel Conduit, by H. E. Frigel and F. A Fisher. General Electric Co., Pittsfield, Mass. (This is a draft-informal working paper).

18. Naval Civil Engineering Laboratory Technical Note N-877: "Guide for Shielded Enclosure Construction Problems". Port Hueneme, California.

19. Conductor Voltages Caused by Pulse Currents Flowing in a Conduit, Part II, H. Fiegel, E. R. Uhlig, General Electric Co., Pittsfield, Mass. 5 Jan 1966.

20. Instruction Manual on the Use of a Shielded Enclosure Leak Detection System, Naval Electronic Systems Command, San Francisco Bay Naval Shipyard, Vallejo, California. 1 Mar 1968.

21. Defense Atomic Support Agency. Electromagnetic Pulse Handbook, DASA 2114-1, Washington D.C., September 1968, with classified supplement 2114-2 (SRD).

UNCLASSIFIED
Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1 ORIGINATING ACTIVITY (Corporate author) NAVAL CIVIL ENGINEERING LABORATORY Port Hueneme, California 93041	2a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED; 2b. GROUP

3 REPORT TITLE
NUCLEAR ELECTROMAGNETIC PULSE PROTECTIVE MEASURES APPLIED TO A TYPICAL COMMUNICATIONS SHELTER

4 DESCRIPTIVE NOTES (Type of report and inclusive dates)
not final; October 1968 to August 1969

5 AUTHOR(S) (First name, middle initial, last name)
H. A. Lasitter
D. B. Clark

6 REPORT DATE	7a. TOTAL NO OF PAGES	7b. NO OF REFS
April 1970	151	21

8a CONTRACT OR GRANT NO N62399-68-C-0031	9a. ORIGINATOR'S REPORT NUMBER(S)
b. PROJECT NO YF 38.534.006.01.015	
c	9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)
d.	

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13 ABSTRACT

A detailed study of a typical communication facility has been made to determine the requirements for the installation of nuclear electromagnetic pulse (NEMP) protection measures. Necessary hardening measures have been determined on the basis of a single point failure analysis and the assignment of priorities to the various systems and components encountered.

Protective devices have been applied to power control and signal lines entering and within the complex as well as to electrically powered life support systems. NEMP hardening techniques and methods have been applied to non-electrical shelter penetrations as necessary and other applicable areas within the facility such as non-strategic lines, grounding systems, and cable routing.

DD FORM 1 NOV 65 1473 (PAGE 1)
S/N 0101-807-6801

UNCLASSIFIED
Security Classification

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
COMMUNICATION EQUIPMENT						
NUCLEAR ENERGY						
ELECTROMAGNETIC PULSES						
PROTECTION						
HARDENED INSTALLATIONS						
FAILURE						
ELECTRIC CURRENT						
ELECTRIC POWER TRANSMISSION						
TELECOMMUNICATION						
SHELTERS						